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TECHNICAL REPORT

Bounding Analysis of Effects of Fractionation of Radionuclides in Fallout on Estimation of Doses to Atomic Veterans

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John R. Trabalka and David C. Kocher

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SENES Oak Ridge, Inc.
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14. ABSTRACT
This report presents a bounding analysis of the effects of fractionation of radionuclides in fallout from atmospheric nuclear-weapons tests on reconstructed radiation doses to atomic veterans. All dose reconstructions for atomic veterans have been performed by assuming that there was no fractionation of radionuclides in fallout, except for removal of noble gases. This report evaluates the potential importance of fractionation in estimating doses to atomic veterans by using assumptions that would be expected to maximize effects of fractionation.

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ABSTRACT

This report presents a bounding analysis of the effects of fractionation of radionuclides in fallout from atmospheric nuclear-weapons tests on reconstructed radiation doses to atomic veterans. All dose reconstructions for atomic veterans have been performed by assuming that there was no fractionation of radionuclides in fallout, except for removal of noble gases. Our purpose was to evaluate the potential importance of fractionation in estimating doses to atomic veterans by using assumptions that would be expected to maximize effects of fractionation. Our approach was to (1) assume complete separation of refractory radionuclides from volatile radionuclides in local fallout and (2) evaluate the effects of this assumption on doses to individuals exposed to fallout containing only refractory radionuclides after decay periods of 2 days and 4 years compared with doses produced by the same pathways of exposure under an assumption of no fractionation. If effects of fractionation on doses are relatively small under bounding conditions at early and late times after detonation, more rigorous calculations to assess effects of fractionation on doses to atomic veterans would not be needed. Exposure pathways considered included external exposure to radionuclides deposited on the skin or ground surface and internal exposure to inhaled or ingested radionuclides. The results of our bounding calculations indicate that reconstructed doses to atomic veterans that assume no effect of fractionation could underestimate actual doses from exposure to fission and activation products by less than a factor of two under the most extreme and highly unlikely assumptions about fractionation. In many cases, however, the current approach of neglecting fractionation in dose reconstructions for atomic veterans probably results in overestimates of doses from exposure to fission and activation products if significant enhancement of refractory radionuclides relative to volatiles occurred. These conclusions do not include the potential effects of contributions from unfissioned plutonium in weapons debris, for which all data are currently classified. However, effects of fractionation on doses from plutonium should be bounded by our analysis, provided levels of plutonium in unfractionated weapons debris have been accurately characterized in carrying out dose reconstructions for atomic veterans. Under these conditions, doses from plutonium would likely be underestimated by less than a factor of three.

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1. INTRODUCTION

In dose reconstructions for atomic veterans, activity concentrations of specific radionuclides in fallout deposited on the ground are estimated on the basis of external exposure rates (R/h) that were measured within a few days after detonations of nuclear weapons by assuming that there was no fractionation of radionuclides, except for removal of noble gases (Egbert et al. 1985; NRC 2003). The term "fractionation" refers to the chemical and physical separation of radionuclides produced in a nuclear detonation as the fireball cools over time. Thus, assumed relative activities of specific radionuclides in fallout are based essentially on estimates of their abundances or abundances of their precursor radionuclides in weapons debris shortly after a detonation and before fractionation occurred (e.g., see Hicks 1982; Hicks 1990; and references therein). For example, relative activities of various fission products in fallout are assumed to be determined by known fission yields (atoms per fission) in the different mass chains produced by fission of plutonium and/or uranium in a weapon and knowledge of the decay rates (half-lives) of radionuclides and precursor-decay product relationships within each mass chain.

The National Research Council's Committee to Review the Dose Reconstruction Program of the Defense Threat Reduction Agency noted that while fractionation typically alters the relative activities of refractory and volatile radionuclides in local fallout by a factor of about 3–4 compared with initial activities in an atmospheric cloud produced by a nuclear detonation, an effect as large as a factor of 100 or greater has been reported (NRC 2003; also see Freiling et al. 1964). Thus, the committee expressed the concern that activities of plutonium and other refractory radionuclides in fallout at locations of exposure of atomic veterans could be underestimated substantially when fractionation is not taken into account, especially at the Nevada Test Site (NTS), and that activities of volatile radionuclides could be overestimated to a similar extent.

Although questions exist about the potential contribution of fractionation to uncertainty in estimated doses to atomic veterans, the limited data on fractionation in weapons fallout do not appear sufficient to fully address the concerns. Therefore, we elected to evaluate the potential importance of fractionation in estimating doses to atomic veterans by using assumptions that would be expected to maximize effects of fractionation. Our analysis is intended to apply

primarily to exposures at locations within a few tens of miles from ground zeros of detonations at the NTS, where substantial enhancement of refractory radionuclides, compared with volatiles, in fallout occurred. However, the results also are applicable to exposures in the Pacific if enhancement of refractories in fallout occurred. We also considered effects of enhancement of volatile radionuclides on estimated doses, but these results are not expected to be important to exposures of atomic veterans at the NTS or in the Pacific.

The following section provides additional discussion of the process of fractionation and its potential significance in dose reconstructions for atomic veterans, as well as the rationale for the approach we used to bound the effects of fractionation on dose. Data sources and equations used in the bounding analysis are described in Section 3, and results of our calculations are presented and discussed in Section 4. A summary of the results and our conclusions about their implications are presented in Section 5. Data used in our analysis are tabulated in Appendix A.

2. BACKGROUND AND APPROACH

Fractionation of radionuclides in fallout is a complex phenomenon (Freiling 1961; Freiling 1963; Freiling et al. 1965), and data on fractionation in fallout from specific nuclear weapons tests do not appear to be extensive. Chemical separation of radionuclides occurs in the first few minutes after a detonation as a result of differences in rates of condensation of the various elements that initially make up the radioactive materials in a fireball. Refractory materials have relatively high boiling points and are largely incorporated in liquid droplets of molten soil and iron oxide that form as materials in the fireball from a near-surface explosion cool to about 3000^{o}C. In contrast, volatile elements are those that have relatively low boiling points or that have precursors with low boiling points and remain in the gaseous phase while the fireball cools to about 1500^{o}C and the liquid droplets solidify. As the cloud cools to ambient temperature (~50^{o}C), volatile elements (except for the noble gases Kr and Xe) and their decay products condense on the surfaces of particles. Radionuclides that exhibit the largest fractionation effects in fallout are those that have short-lived isotopes of Kr and Xe as precursors; those radionuclides include, for example, Sr-89, Sr-90, and Cs-137 (Hicks 1982; NRC 2003).

Physical separation of fission products occurs as a result of differences in the settling velocities of small and large particles in the atmosphere. Fallout close to ground zero consists mostly of relatively large particles that contain a higher proportion of refractory materials, whereas fallout at more distant locations consists mostly of relatively small particles that contain a larger proportion of volatile radionuclides (NRC 2003).

An assumption of no fractionation (other than removal of noble gases) in fallout should result in overestimates of the concentrations of volatile radionuclides deposited on the ground at locations of exposure of atomic veterans but underestimates of refractory radionuclides, because participants at the NTS and the Pacific Proving Grounds usually were exposed at locations where fallout was dominated by larger particles that should have contained a higher proportion of refractory radionuclides (NRC 2003). An assumption of no fractionation also does not account for differential fractionation of the volatile radionuclides Sr-89, Sr-90, and Cs-137, which results from differences in the half-lives of their noble-gas precursors (NRC 2003).

A simplified and idealized description of fractionation is given by Hicks (1982). Hicks assumed that mass chains of fission products produced by nuclear detonations are either all

refractory (mass chains 92–100 and 142–180) or all volatile (75–90 and 101–139), except for mass chains 91, 140, and 141, which he characterized as having precursors that exhibit volatile and refractory behavior. Hicks also classified activation products in mass chains 181–203 as volatile and those in mass chains 7–74 and 204–242 as refractory, while noting that there were no known volatile radionuclides within the latter two mass ranges.

For purposes of estimating concentrations of radionuclides in fallout at locations far from the NTS, Hicks (1982) also concluded that the limited data on fractionation were consistent with a 50% removal of refractory radionuclides but no removal of volatiles in fallout within 160 miles of ground zero. However, no data on the extent of fractionation in fallout from NTS shots were reported for distances less than 5–15 miles from ground zero, which is a region of interest in dose reconstructions for atomic veterans at the NTS. Data presented by Hicks, which show that volatile/refractory ratios increased with increasing distance and with decreasing particle size, indicate that concentrations of refractories relative to volatiles had to be elevated within the region closest to ground zero.[1] Indeed, Hicks' conclusion would imply that at some point close to ground zero, fallout would have consisted almost entirely of refractory radionuclides, which typically are incorporated within the volume of larger fallout particles, and it suggests that a bounding analysis of effects of fractionation on estimated doses to atomic veterans that assumes complete separation of refractory and volatile radionuclides in local fallout is not unreasonable.

Given the paucity of data on fractionation of radionuclides in fallout at locations of exposure of atomic veterans at the NTS, our approach was to (1) assume complete separation of refractory radionuclides from volatile radionuclides in local fallout and (2) evaluate the effects of this assumption on estimated doses to individuals exposed to fallout containing only refractory radionuclides compared with doses produced by the same pathways of exposure under an assumption of no fractionation, as is currently used in dose reconstructions for atomic veterans. Our reasoning was that if effects of fractionation on doses, in contrast to relative activities of individual radionuclides or groupings of radionuclides, are relatively small under such conditions, more rigorous calculations to assess effects of fractionation on doses to atomic veterans would not be needed.

[1] The study that provided the primary source of data used by Hicks (Larson et al. 1966) also showed significant fractionation of Sr-89 from Sr-90 in close-in fallout from tower shots (defined as fallout that occurred in the zone beginning at one mile from ground zero and continuing out to the distance at which fallout arrived at 12 hours after detonation).

In dose reconstructions for atomic veterans, relative concentrations of fission products in fallout from fission of Pu-239, U-235, and U-238 by fast and high-energy (14-MeV) neutrons are obtained by combining classified data on yields of nuclear weapons from different fission modes with unfractionated fission product inventories for each fission mode provided by the computer program FIIDOS (Egbert et al. 1985). Fission product inventories in FIIDOS were calculated with the isotope generation and depletion code ORIGEN2 by assuming an instantaneous (2 msec) irradiation time. Each inventory includes the activities of 148 radionuclides potentially produced in fission. For a particular nuclear test, those inventories are adjusted based on the fraction of the total fissions attributable to a given fission mode (e.g., from fast neutron fission of U-235), as obtained from yield data specific to that test. Each fission product inventory is calculated at 40 decay times ranging from 3 minutes to 70 years (Egbert et al. 1985).

Data on the amounts of activation products and actinides initially produced by a weapon are supplied by the user of the FIIDOS code. Inventories of individual activation products and actinides are normalized to 10^{14} fissions and calculated at the decay times just described.

For calculations involving fallout deposited on the ground, 13 isotopes of Kr and Xe are removed from the radionuclide inventory. Provisions to modify the radionuclide composition to reflect fission product fractionation are included in the FIIDOS code but reportedly have not been used in dose reconstructions for atomic veterans (Egbert et al. 1985; NRC 2003).

Since we lacked access to the FIIDOS or ORIGEN2 codes, we performed simplified calculations to estimate radionuclide inventories and doses for various exposure pathways using spreadsheet models. The pathways considered included external exposure to radionuclides deposited on the skin or ground surface and internal exposure to inhaled or ingested radionuclides (see Section 3). Calculations were performed for post-detonation times of 2 days and 4 years, which we assume can be used to bound the effects of fractionation in fresh fallout and in aged fallout, respectively. The results at 2 days are relevant to evaluating the effects of fractionation on estimates of concentrations of radionuclides on the ground surface, because photon exposure rates in air on which those estimates were based were measured at times within a few days after detonation. Results at 4 years are relevant to certain scenarios for inhalation exposure of atomic veterans at the NTS that involved unusually high resuspension of aged fallout, either by the precursor or blast wave produced in a detonation or by participation in certain types of maneuvers (e.g., helicopter landings) (NRC 2003; Kocher et al. 2005).

3. DATA AND METHODS

3.1 DOSE MODELS AND SOURCES OF DATA

We carried out a series of simplified calculations based on an assumption that local fallout contained only refractory radionuclides for the purpose of estimating doses resulting from various pathways of internal and external exposure to fission products and a limited suite of neutron activation products produced by detonation of nuclear weapons compared with doses that would result by assuming that fallout was unfractionated.

To perform the calculations needed for our evaluation of the effects of fractionation on estimates of dose to atomic veterans, we utilized five sets of information:

- Fission yields of radionuclides from four fission modes in nuclear weapons:
  - U-235 by fission neutrons.
  - Pu-239 by fission neutrons.
  - U-238 by fission neutrons.
  - U-238 by 14.7 MeV neutrons.
- Yields of neutron activation products.
- Data on decay chains for fission and neutron activation products.
- Dose coefficients for internal exposure to radionuclides via inhalation or ingestion (i.e., committed doses per unit activity intake):
  - Effective doses from inhalation or ingestion, which give a sum of weighted equivalent doses in various organs and tissues of the body (ICRP 1991).
  - Doses to the lung, red marrow, and pancreas from inhalation.
  - Doses to the colon, red marrow, and pancreas from ingestion.
- Dose coefficients for three pathways of external exposure to radionuclides (i.e., dose rates per unit activity concentration in specified source region):
  - Dose to the skin from electrons emitted by radionuclides deposited on the skin.
  - Dose to the skin from electrons emitted by radionuclides deposited on the ground.
  - Effective dose equivalent from photons emitted by radionuclides deposited on the ground.
- Hicks' (1982) categorization of volatile and refractory radionuclides (see Section 2).

The types and sources of this information are discussed in Sections 3.2–3.4. An emphasis on external exposure of the skin to electrons emitted by radionuclides deposited on skin or on the ground reflects the importance of skin cancers in claims for compensation by atomic veterans.

In performing the calculations, we eliminated parameters that were not needed in assessing effects of fractionation on dose, so that results would not be confounded by uncertainties in other parameters (e.g., inhalable fraction, resuspension factor) used in dose calculations for specific pathways. The importance of uncertainties in such parameters in assessing doses to atomic veterans is evaluated in other studies (e.g., see Apostoaei and Kocher 2005; Kocher et al. 2005).

The basic equations used in the dose calculations are the following:

$$\mathbf{A_{i,j} = SA_i \times FY_{i,j} \times [BDF_i \times BR_i]}, \quad (1)$$

where

$\mathbf{A_{i,j}}$ = activity of radionuclide i per fission in fission mode j (Bq/fission),

$\mathbf{SA_i}$ = specific activity of radionuclide i or appropriate precursor (Bq/atom),

$\mathbf{FY_{i,j}}$ = fission yield of radionuclide i or appropriate precursor in fission mode j (atom/fission),

$\mathbf{BDF_i}$ = buildup-decay factor for radionuclide i (dimensionless),

$\mathbf{BR_i}$ = branching ratio for production of radionuclide i in decay of precursor (dimensionless).[2]

$$\mathbf{D_{i,j} = A_{i,j} \times DF_i} \quad (2)$$

where

$\mathbf{D_{i,j}}$ = effective dose from intake of radionuclide i produced in fission mode j (Sv/fission),

$\mathbf{A_{i,j}}$ = activity of radionuclide i per fission (Bq/fission) in fission mode j [see equation (1)], which is activity assumed to be inhaled or ingested,

$\mathbf{DF_i}$ = effective dose per unit activity intake of radionuclide i by inhalation or ingestion (Sv/Bq).

[2] The activity of some radionuclides represents the sum of activities resulting from decays of precursors with two decay modes (i.e., with different buildup-decay factors and branching ratios) and, in several cases, from decays of several precursors with independent fission yields (e.g., I-131); see discussion in Section 3.3 and data in Appendix A, Tables A.1 and A.2.

$$\mathbf{D_{i,j,k} = A_{i,j} \times DF_{i,k}} \quad (3)$$

where

$\mathbf{D_{i,j,k}}$ = equivalent dose to organ/tissue k from intake of radionuclide i produced in fission mode j (Sv/fission),

$\mathbf{A_{i,j}}$ = activity of radionuclide i per fission (Bq/fission) in fission mode j [see equation (1)], which is activity assumed to be inhaled or ingested,

$\mathbf{DF_{i,k}}$ = equivalent dose to organ/tissue k per unit activity intake of radionuclide i by inhalation or ingestion (Sv/Bq).

$$\mathbf{D_{i,j,m} = A_{i,j} \times DF_{i,m},} \quad (4)$$

where

$\mathbf{D_{i,j,m}}$ = dose rate to skin or whole body from external exposure to radionuclide i produced in fission mode j via exposure pathway m, which is assumed to be exposure to contaminated skin or ground surface (Sv/h per fission/cm^2),

$\mathbf{A_{i,j}}$ = activity of radionuclide i per fission (Bq/fission) in fission mode j [see equation (1)], which is assumed to be activity per unit concentration on skin or ground surface,

$\mathbf{DF_{i,m}}$ = dose rate to skin or whole body per unit activity concentration of radionuclide i on skin or ground surface (Sv/h per Bq/cm^2).

In equation (4), the dose rate to the whole body from external exposure to a contaminated ground surface is assumed to be given by the effective dose rate. As noted previously, dose rates to skin are dose rates from external exposure to electrons only.

Similar calculations were performed for neutron activation products. For each pathway and fission mode, doses from individual radionuclides in three groupings (refractories, volatiles, and unfractionated mixtures) were then summed. The values for the parameters used are given in Tables A.1–A.6 of Appendix A and the overall approach is shown schematically in Figure 1. Further details of the dose calculations and use of the results to evaluate the effects of fractionation are given in Section 3.5.

3.2 RADIONUCLIDE INVENTORIES AND DECAY CHAINS

3.2.1 *Fission Yields and Decay Chains for Fission Products*

Information on decay chains and yields of fission products was obtained from England and Rider (1994) for four fission modes: U-235 by fission neutrons (U-235 n_f), Pu-239 by fission neutrons (Pu-239 n_f), U-238 by fission neutrons (U-238 n_f), and U-238 by 14.7-MeV neutrons (U-238 n_{14}). These data were expected to represent the principal fission modes of interest in assessing doses from exposure to weapons fallout. In the absence of actual or generic nuclear weapons yield data, we were not able to estimate the fractional contributions of each fission mode to the total fission yield for specific shots. Thus, we performed four independent sets of calculations using these data, one for each fission mode. Fission yield data for specific radionuclides used in the calculations are shown in Tables A.3 and A.4 of Appendix A.

Fission products with half-lives of 2.4 hours or less were not included unless they were required in calculating the activities of longer-lived decay products (e.g., 23-min Sb-131, 2.1-h Sn-127) or they were decay products of long-lived radionuclides (see Section 3.3and listing of half-lives in Table A.1 of Appendix A). Radionuclides with half-lives greater than 10^4 years (e.g., 6.5×10^4-y Se-79) also were excluded because they were expected to make negligible contributions to doses and dose rates in the time frames considered, due to their low specific activities. Noble-gas fission products (isotopes of Kr and Xe) were excluded regardless of half-life because they were not present in fallout. Radionuclides with fission yields less than 10^{-6} were excluded unless the yield for at least one of the four fission modes exceeded 10^{-6} (e.g., Cd-113m, I-130). Finally, contributions from 7.4-min Pr-144m, which is a decay product of Ce-144, were ignored because that radionuclide contributes negligibly to internal and external doses from exposure to Ce-144 and its decay product Pr-144.

3.2.2 *Neutron Activation Products*

In contrast to the situation for fission products, there is much less published information on yields of activation products from nuclear detonations. Published data for specific activation products produced by individual nuclear detonations are limited to activation products in weapons debris, and those data that are available appear to be highly variable (e.g., see

Morgenthau et al. 1957; Hicks 1981). Hicks (1982) assumed a yield of one atom of each activation product per fission in his calculations. Calculations presented in this report that include neutron activation products consider U-237 and U-239–Np-239 only. However, as indicated by later discussions in Section 4.1, we believe that calculations that include uranium activation products are sufficient to fully support a bounding analysis of the effects of fractionation on reconstructed doses to atomic veterans.

Yields of U-237 and U-239─Np-239 in one set of calculations for all fission modes (fission products + U, 2-d decay) were based on activation estimates of 0.15 atoms/fission for U-237 and 0.30 atoms/fission for U-239 in fallout resulting from Shot BRAVO, which was a test of a thermonuclear weapon (Miller 1964). Based on the results for effective dose rates from exposure to radionuclides on the ground surface that include U-237 and U-239 at the stated levels (see Section 4.1), however, it appears that the activation estimates from the Shot BRAVO data cited by Miller (1964) may not be representative of levels in fallout from many thermonuclear weapons tests. Decay of U-237 and Np-239 in fallout from thermonuclear weapons reportedly can contribute 50% or more of the total gamma radiation level at times of a few days after detonation (Miller 1959; Barss 2000). However, results of calculations based on the Shot BRAVO data yield an increase in the effective dose rate from ground deposition of fallout, which is a reasonable surrogate for external gamma radiation level, of only about 14% compared with calculations that include fission products only. The yield of Na-24, which is the other principal activation product in weapons debris, and its contribution to the external exposure rate was found to be small in comparison with uranium activation products and fission products produced in fission and thermonuclear devices tested in the Pacific (Miller 1959).

Data on Np-239 levels in fallout following several weapons tests conducted during Operation REDWING in May–July 1956 at the Pacific Proving Grounds were provided by Morgenthau et al. (1957). Measurements of Mo-99 (a refractory fission product) and Np-239 (also considered to be refractory) were used to estimate the yields of Np-239 per fission in fallout from three tests. Values ranged from about 0.2 atoms/fission for fallout from Shot LACROSSE (40 kt) to about 0.5–1 atoms/fission (including uncertainties) for Shots ZUNI (3.5 Mt) and FLATHEAD (also presumed to be a multi-Mt device, although no yield was provided in any reference available to us, e.g., Zander and Araskog 1973; Moghissi and Carter 1977). Thus, we performed another set of calculations for all fission modes by assuming elevated levels of

uranium activation products (fission products + 3.3 × U, 2-d decay); the yield of Np-239 in those calculations was increased from 0.3 to 1 atom/fission, and the yield of U-237, which was not measured in the fallout studies at Operation REDWING, was increased to 0.5 atoms/fission based on its relative abundance in the Shot BRAVO fallout data. These increases resulted in an increase in the effective dose rate from ground deposition of fallout of about 50% compared with calculations that include only fission products, in better agreement with the expected contribution of uranium activation products to gamma radiation levels in fallout from thermonuclear weapons tests.

Although calculations were performed for all fission modes using the two sets of U-237 and Np-239 data described above, much of the data are strictly applicable only to activation of U-238 in the uranium tamper of a thermonuclear weapon, for which the principal source of neutrons is expected to be fusion reactions (~14 MeV) and fission of U-238 by ~14-MeV and fission neutrons. However, a complete set of results for all four fission modes was included because they show that (1) assumptions about relative contributions from other fission modes have little or no effect on conclusions about effects of fractionation obtained from comparisons of estimated doses for U-238 n_{14} fission alone and (2) results of calculations that include Np-239 and U-237 appear to bound the effects of fractionation that would be obtained on the basis of other assumptions about quantities of activation products (see Section 4.1).

Comparisons of data provided by Hicks (1981) on Np-239, U-237, and Mo-99 activity levels in fallout from four detonations of fission weapons conducted during Operation PLUMBBOB in 1957 [BOLTZMANN (12 kt), FRANKLIN (0.14 kt), PRISCILLA (37 kt), and WILSON (10 kt)] suggest that the yield of Np-239 in these tests was less than about 0.1 atoms/fission, and that the yield of U-237 was an order of magnitude lower. We did not have access to all the data on tests at the NTS that have been compiled in the series of reports by Hicks. However, coupled with the data on the yield of Np-239 (about 0.2 atoms/fission) in Shot LACROSSE (40 kt) at Operation REDWING and additional data on the relative importance of activation products given by Hicks (1982), it would appear that the data for Shot BRAVO might be a useful surrogate (i.e., perhaps close to an upper bound) for levels of uranium activation products in fallout from weapons tests at the NTS. Neptunium-239 reportedly was the primary source of gamma radiation among the activation products in those tests, contributing up to 20% of external gamma radiation levels from early fallout (e.g., in fallout from Shots HARRY and SMOKY; Hicks et al. 1982). Such

levels are comparable to those produced by U-237 and Np-239 combined in fallout from Shot BRAVO, as discussed above.

Uranium-237 and Np-239 were not included in calculations in which a 4-year decay period was assumed because of their very short half-lives (both less than 10 days). Other short-lived uranium activation products that could be considered at 2 days are U-240 and Np-240m. However, available information (e.g., Hicks 1981) indicates that yields of these radionuclides were typically 1–2 orders of magnitude less than yields of U-237 or U-239–Np-239.

The effects of not including activation products in weapons debris other than those of uranium are not expected to be substantial, because data reported by Hicks (1982) indicate that contributions to photon exposure rates in air from other activation products in fallout at the NTS were less than exposure rates from Np-239. For example, the contribution to exposure rates from Co-60, which is the next most important activation product, was 10% or less (Hicks 1982). A check of the NTS data for 25 detonations (tower shots, balloon shots, air bursts) by Hicks (1982) reportedly showed that contributions of more than 1% to the total gamma radiation levels were due to only three activation products: Co-60, U-237, and Np-239. Contributions from other activation products to other exposure pathways, such as inhalation, should be of the same order of magnitude. However, additional calculations could be performed to include such materials if so desired.

3.3 RADIOACTIVE DECAY CALCULATIONS

Calculations of activities (in units of Bq/fission) of each fission and uranium activation product were performed for each of the four fission modes, as indicated in Figure 1, using an EXCEL spreadsheet program. Initial activities were corrected for radioactive decay over times after detonation times of 2 days and 4 years. Analyses at these times are expected to provide representative information on conditions at times of interest in exposures of atomic veterans.

Two sets of calculations included assumed activities of uranium activation products, as estimated from yields in tests conducted in the Pacific (see Section 3.2.2), and the other set of calculations included only data on yields of fission products. Parameters used in the decay calculations are given in Tables A.1 and A.2 of Appendix A, along with calculated buildup-decay factors and decay branching ratios with values less than 1.

Because we did not have access to a sophisticated isotope generation and depletion code, such as ORIGEN2, as used in FIIDOS (Egbert et al. 1985), we calculated buildup and decay of radionuclides in decay chains directly using the Bateman equations, as described in Evans (1955). This approach can be problematic when a mass chain has decay products with significant fission yields independent of yields of the parent or other precursor radionuclides (see Table A.3 of Appendix A) and calculations involving decay chains longer than three radionuclides can be difficult to perform analytically. Thus, as described below, simplifications were employed to reduce the complexity of decay-chain calculations or eliminate radionuclides that were not expected to be significant contributors to fission product activity.

- As noted in Section 3.2.1, radionuclides with half-lives less than 2.4 hours were not included in calculations unless they are decay products of radionuclides with half-lives of 2.4 hours or greater. The rationale for this choice was that more than 10 half-lives would have elapsed in the 2-day decay period assumed in the first set of calculations. Likewise, radionuclides with half-lives less than 30 days were not included in the calculations at 4 years unless they are decay products in secular equilibrium with longer-lived parents. Radionuclides with half-lives greater than 10^4 years also were excluded, as noted in Section 3.2.1, due to their very low activities per fission compared with shorter-lived radionuclides.
- Effects on yields and activities due to decay of short-lived precursors with half-lives less than 10 minutes were ignored, because the effects were expected to be negligible.
- In the following three cases, consideration of four-member decay chains was required:
  - 10-min Y-95 → 64.02-d Zr-95 → 86.6-h Nb-95m → 35.06-d Nb-95
  - 2.1-h Sn-127 → 3.85-d Sb-127 → 109-d Te-127m → 9.35-h Te-127
  - 23-min Sb-131 → 30-h Te-131m → 25-min Te-131 → 8.04-d I-131.

  Calculations at 2 days for the first two cases were simplified by reducing the decay period by an amount equal to the time of maximum buildup of the decay product of the first radionuclide in the decay chain, which is given by $t_{max} = \ln (\lambda_A/\lambda_B)/(\lambda_B - \lambda_A)$, where λ_A and λ_B are the decay constants for the first and second radionuclides in the decay chains, respectively (Evans 1955). Thus, the decay periods in the 2-day calculations were reduced by 2.2 hours for Zr-95 and by 11.7 hours for Sb-127, to 45.8 hours and

36.3 hours, respectively. In the third case, the branching ratio for the portion of the decay pathway from 30-h Te-131m to 8.04-d I-131 was increased from 0.778 to 1 to account for the contribution from intermediate decay of 25-min Te-131. This simplification is expected to have a negligible influence on the results because the half-life of Te-131 is about 1% of that for Te-131m and about 0.2% of that for I-131 (see Table A.2 of Appendix A).

- Ag-111 is fed by decays of 5.5-h Pd-111m and 23-min Pd-111, both of which originate from decay of the fission product 11-s Rh-111. Because the branching ratio from Rh-111 to Pd-111m is <0.5%, the presence of Pd-111m and its decay products, 23-min Pd-111 and 74-s Ag-111m, was ignored in mass chain 111, and Pd-111m was not included in the calculations even though its half-life is greater than 2.4 hours. A similar simplification apparently is employed in the FIIDOS code (see Table 7 in Egbert et al. 1985).

These types of assumptions and simplifications are not expected to have a significant impact on the results of our analysis. For example, results from the present exercise were not significantly different than those from a preliminary set of calculations we performed that did not include decay chain calculations for any precursor with a half-life less than 2.4 hours. If greater rigor is desired, we would need access to a computer program, such as ORIGEN2, to calculate the formation, buildup, and decay of fission products, along with weapons yield data for different fission modes.

Using the approaches described in Section 2.1 and this section, the total number of fission products was reduced to 79 in the 2-day calculations and to 27 in the 4-year calculations. Radionuclides (fission and activation products) included in the calculations at 2 days and 4 years are listed in Table 1.

3.4 EXTERNAL AND INTERNAL DOSE COEFFICIENTS

3.4.1 *Dose Coefficients for External Exposure*

As discussed in Section 3.1, we performed dose calculations for three pathways of external exposure using equation (4). External dose coefficients for the 79 fission products and two activation products included in our analysis were obtained from the published literature for the following exposure pathways:

- Exposure of the skin to electrons emitted by radionuclides deposited on the surface of the body;
- Exposure of the skin to electrons emitted by radionuclides deposited on the ground surface;
- Exposure of the whole body to photons emitted by radionuclides deposited on the ground surface.

These pathways were selected because skin can receive the largest dose from exposure to radionuclides deposited on the body surface or ground and the effective dose rate resulting from photons emitted by radionuclides deposited on the ground is a reasonable surrogate for the photon exposure rate in air, which is used to calculate concentrations of radionuclides in fallout in dose reconstructions for atomic veterans (Barrett et al. 1986; NRC 2003). However, only the results at 2 days are relevant to evaluating the effects of fractionation on estimates of concentrations of radionuclides on the ground surface, because photon exposure rates in air on which those estimates were based were measured within a few days after detonation. Doses to skin from exposure to photons emitted by radionuclides deposited on the body surface or ground are not included because they are unimportant whenever a radionuclide emits significant intensities of electrons, primarily beta particles, of energy sufficient to irradiate tissue at a depth of 7 mg/cm^2.

3.4.1.1 *Dose Rate to Skin from Radionuclides Deposited on Body Surface.*

Dose coefficients for exposure of the skin to electrons emitted by radionuclides deposited on the surface of the body were obtained from Table 1 in Kocher and Eckerman (1987). Those dose coefficients apply to irradiation of tissue at a depth of 7 mg cm^{-2}, and they were calculated by

assuming that sources are distributed uniformly on the body surface.[3] However, Kocher and Eckerman (1987) did not provide dose coefficients for the following 27, mainly shorter-lived, radionuclides included in our calculations: Ge-77, As-77, Y-91m, Sr-92, Y-92, Y-93, Pd-109, Ag-111, Ag-112, Ag-113, Cd-115, In-115m, Sn-121, Sn-123, Sn-125, Sb-128, I-130, La-141, Pr-145, Pm-149, Pm-151, Sm-153, Sm-156, Eu-156, Eu-157, Gd-159, and U-237. Dose coefficients for these radionuclides were estimated by interpolation of values in Kocher and Eckerman (1987) for radionuclides with similar average or maximum beta energies. Interpolations were based on maximum beta energies when average beta energies were not available. Average beta energies were obtained from Kocher (1980), and maximum beta energies were obtained from Kocher (1981) or Firestone (1996).

Dose coefficients obtained from data in Kocher and Eckerman (1987) in units of Sv/y per Bq/cm^2 were converted to units of Sv/h per Bq/cm^2 by dividing by 8760. Dose coefficients for exposure of the skin to electrons emitted by radionuclides deposited on the surface of the body used in our analysis are given in Table A.5 of Appendix A.

3.4.1.2 *Dose Rate to Skin from Radionuclides Deposited on Ground Surface.*

Dose coefficients for exposure of the skin to electrons emitted by radionuclides deposited on the ground surface were obtained from Table III.3 in Eckerman and Ryman (1993). Those dose coefficients were calculated at a height of 1 m above ground and assume exposure to an infinite and uniformly contaminated plane source. However, the compilation by Eckerman and Ryman (1993) does not include two radionuclides considered in our analysis: Pd-112 and Ag-113. Dose coefficients for these two radionuclides were estimated by interpolation of values in Eckerman and Ryman (1993) for radionuclides with similar decay schemes. In the case of Pd-112, dose coefficients for Pd-113 and Cf-253 were summed to obtain a suitable surrogate and, for Ag-113, dose coefficients for Ag-110 and Sm-153 were summed. These summations were required because decay schemes of single radionuclides alone were insufficiently representative of the decay schemes of Pd-112 and Ag-113.

[3] An assumption of uniform contamination over the body is not a serious limitation in using dose coefficients calculated by Kocher and Eckerman (1987). As a result of the short range of electrons in tissue, a surface area as small as 15 cm^2 is effectively infinite in extent with respect to estimating electron dose to skin at depths below the center of a contaminated area.

Dose coefficients obtained from data in Eckerman and Ryman (1993) in units of Sv/s per Bq/m^2 were converted to units of Sv/h per Bq/cm^2 by multiplying by 3.6×10^7. Dose coefficients for exposure of the skin to electrons emitted by radionuclides deposited on the ground surface used in our analysis are given in Table A.5 of Appendix A.

3.4.1.3 *Effective Dose Rate from Radionuclides Deposited on Ground Surface.*

Effective dose coefficients for exposure to photons emitted by radionuclides deposited on the ground surface also were obtained from Table III.3 in Eckerman and Ryman (1993). Those dose coefficients again were calculated at a height of 1 m above ground and assume exposure to an infinite and uniformly contaminated plane source. As discussed in the previous section, dose coefficients in Eckerman and Ryman (1993) do not include values for Pd-112 and Ag-113, and dose coefficients for these radionuclides again were estimated by interpolation of values for other radionuclides.

Dose coefficients obtained from data in Eckerman and Ryman (1993) in units of Sv/s per Bq/m^2 again were converted to units of Sv/h per Bq/cm^2 by multiplying by 3.6×10^7. Effective dose coefficients for exposure to photons emitted by radionuclides deposited on the ground surface used in our analysis are listed in Table A.5 of Appendix A.

3.4.2 *Dose Coefficients for Internal Exposure*

All dose coefficients for inhalation or ingestion of radionuclides used in dose reconstructions for atomic veterans are 50-year committed doses, i.e., equivalent doses delivered to specific organs or tissues over 50 years following a single intake. Those dose coefficients were obtained from Publication 30 of the International Commission on Radiological Protection (ICRP 1979) or from reports by Killough et al. (1978) and Dunning et al. (1979), which used dosimetric and biokinetic models similar to those in ICRP Publication 30.

In our analysis, we used organ-specific internal dose coefficients for all radionuclides listed in Table 1 that were calculated using dosimetric and biokinetic models currently recommended by the ICRP (1994a; 1996; and references therein) and were obtained from an available compact disc (ICRP 2002). These dose coefficients are intended to supersede values calculated using

models in ICRP Publication 30 (ICRP 1979). Dose coefficients for adult workers in ICRP Publication 68 (ICRP 1994a) and adult members of the public in ICRP Publication 72 (ICRP 1996) were used. Although dose coefficients for workers may be more appropriate for exposures of atomic veterans, use of both sets of data ensures that potential effects of fractionation on estimated inhalation and ingestion doses were fully considered. Because it was impractical to perform calculations of internal dose to all organs and tissues, we selected a few organs that are expected to be important in inhalation and ingestion exposures, as described below. We also performed calculations using effective dose coefficients to provide a measure of the effects of fractionation on a weighted average of doses to many organs and tissues.

Doses to atomic veterans from ingestion of radionuclides are expected to be small in nearly all cases (NRC 2003). However, in the model of the respiratory tract used in dose reconstructions (ICRP 1979), dose coefficients for inhalation of particles with an activity median aerodynamic diameter (AMAD) of 20 μm, which are used in dose reconstructions when this choice results in a higher estimate of dose to a tissue or organ of concern (NRC 2003), are essentially the same as dose coefficients for ingestion, because about 95% of the inhaled material is assumed to be transferred to the gastrointestinal (GI) tract by swallowing.[4] Thus, we included doses from ingestion of radionuclides, as well as inhalation, in our evaluation of potential effects of fractionation on estimated doses.

For each intake pathway, we used dose coefficients for three organs or tissues: lung, red marrow, and pancreas for inhalation; and colon, red marrow, and pancreas for ingestion. The lung and the colon usually are the organs that receive the highest dose from inhalation of smaller particles (AMAD 1 μm) and ingestion (or inhalation of large particles), respectively, when radionuclides are largely insoluble, as is typically the case in local fallout.[5] Red marrow was included because of the presence of a significant number of bone-seeking radionuclides in fallout and the association between exposure of red marrow and leukemia. The pancreas was included as a surrogate for the prostate, which is a frequent cancer site in claims for compensation by atomic veterans; both organs are assigned to the Remainder Tissues category by the ICRP for

[4] In the ICRP's current lung model (ICRP, 1994b), only about 25% of large particles inhaled is assumed to be transferred to the GI tract by swallowing.

[5] In dose reconstructions for atomic veterans, all inhaled or ingested radionuclides are assumed to be in oxide form (Egbert et al. 1985); such forms are relatively insoluble for all elements of concern except Sr.

purposes of calculating effective doses and should have similar internal dose coefficients when they are not major sites of deposition of radionuclides of potential importance in fallout.

Lung absorption types appropriate for radionuclides in oxide form, as given in Annex F of ICRP (2002), were used to select inhalation dose coefficients, and GI-tract absorption fractions (f_1) appropriate for radionuclides in oxide form, as given in Annex E of ICRP (2002), were used to guide the selection of ingestion dose coefficients. In the case of uranium, which has more than two potential oxide forms, dose coefficients that apply to UO_2 and U_3O_8 were selected.

Because internal dose coefficients for Pd-112 and Ag-113 were not included in ICRP (2002), values used in our analysis were estimated on the basis of dose coefficients for other radioisotopes of the same elements. In the case of Pd-112, which has a decay scheme different from other radioisotopes of Pd (Firestone 1996; see also Section 3.4.1.2), we used dose coefficients for Pd-100 because they are the highest of the values for any radioisotope of Pd included in ICRP (2002) and, thus, should be a suitably conservative surrogate. Dose coefficients for Ag-113 were estimated by dividing values for Ag-112 by a factor of two. This approximation is reasonable when the half-lives of the two radioisotopes are similar (5.3 hours vs 3.13 hours; Firestone 1996) but the maximum beta energy of Ag-112 is about twice that of Ag-113 (3.956 MeV vs 2.016 MeV; Firestone 1996).

Organ- or tissue-specific dose coefficients for inhalation and ingestion of radionuclides used in our analysis are given in Table A.6 of Appendix A and effective dose coefficients are given in Table A.5.

3.5 CALCULATIONS OF EXTERNAL AND INTERNAL DOSE

The first step in the bounding analysis was the calculation of doses per fission from external and internal exposures to fission products and a limited set of uranium activation products in fallout for each assumption about the extent of fractionation in fallout. These calculations were performed for each of four cases:

- Exposure to 79 fission products at 2 days after detonation;
- Exposure to 79 fission products and levels of two uranium activation products derived from data at Shot BRAVO at 2 days after detonation (see Section 3.2.2);

- Exposure to 79 fission products and elevated levels of two uranium activation products (i.e., 3.3 times the levels used in the preceding case, or 1 atom/fission of Np-239 and 0.5 atoms/fission of U-237) at 2 days after detonation;
- Exposure to 27 fission products at 4 years after detonation.

As noted previously, radionuclide-independent factors, such as resuspension factors, deposition rates of resuspended radionuclides on the skin, breathing rates, and duration of exposure, are not needed in evaluating effects of fractionation or differences in fission mode on doses and, thus, were omitted to simplify the calculations. Additional assumptions include the following:

- All radionuclides in fallout are resuspended, and redeposited on the skin, to the same extent. Depending on the stress that causes resuspension of fallout deposited on the ground surface, this assumption may not be correct if near-field fallout enriched in refractory radionuclides has a significantly larger particle-size distribution than fallout enriched in volatile radionuclides. However, the expected effect would be to lower internal doses from intakes of refractories and external doses from deposition of refractories on the skin relative to doses from volatiles, and thus lessen the likelihood that dose calculations assuming no fractionation would yield underestimates of doses.
- Differences in absorption of radionuclides from the lungs or GI tract into blood due to volumetric occlusion of refractory radionuclides within fallout or soil particles compared with absorption of volatile radionuclides that are attached to the surfaces of fallout particles are not considered. Again, the expected effect would likely be to lower internal doses from intakes of refractories relative to those from volatiles, and thus lessen the effects of fractionation, as above.

As noted in Section 3.1, we placed each radionuclide into one of three categories—volatile, refractory, or intermediate—using the approach of Hicks (1982). Our rationale was that this approach would maximize the potential importance of fractionation effects and, thus, would be consistent with the objective of a bounding analysis. That is, if many radionuclides characterized as either purely volatile or purely refractory actually exhibited intermediate (both volatile and

refractory) behavior, as has been suggested by others (e.g., Prokofiev and Smirnov 2000), the effects of fractionation would be reduced. Another justification for our approach is that current data on fractionation of radionuclides do not permit a firm characterization of such intermediate behavior. The assumed categorization of the volatile/refractory behavior of each radionuclide is given in Table A.1 of Appendix A.

One difference between our approach and that of Hicks (1982) is that we apportioned the activity (hence resulting doses) of radionuclides in the intermediate category (identified as V-R in Table A.1) equally between the volatile and refractory fractions of radionuclides in fallout. This assumption was used because fractionation data for debris from nuclear weapons tests given by Crocker et al. (1965), Freiling (1961), and Freiling et al. (1965) suggest that radionuclides in mass chains 91, 140, and 141 exhibit fully intermediate fractionation behavior. Although Hicks (1982) apportioned more of the activity in mass chains 91 and 140 to the volatile category than the refractory category, and did the reverse for mass chain 141, his supporting data were limited and highly variable. Thus, we opted for a simpler approach in dealing with these mass chains. Our approach also increases the total activity of radionuclides in the refractory category, compared with the approach used by Hicks.

Dose calculations were performed using a simple, stepwise, multiplicative-chain model represented by equations (1)–(4). First, for each radionuclide listed in Table 1, the fission or activation yield of that radionuclide and its precursor radionuclides (if any) for a given fission mode, the specific activity of that radionuclide and any precursors, and appropriate correction factors for buildup and decay were multiplied to obtain the activity initially produced by a single fission that was remaining at the time of interest (either 2 days or 4 years after detonation). The activity of each radionuclide at the time of interest was then multiplied by the appropriate dose coefficients for the target organs or tissues and exposure pathways of interest to obtain estimates of dose per fission resulting from internal exposure or dose rate per fission resulting from external exposure.[6]

For each combination of fission mode and exposure pathway, the next step was to calculate total internal doses or external dose rates per fission at 2 days and 4 years for each of the three fractionation categories, i.e., volatiles, refractories, and unfractionated mixtures (see Figure 1).

[6] We describe these quantities as a dose or dose rate per fission, even though they are only proportional to dose or dose rate. Factors of proportionality are unimportant in comparing doses in different cases.

We apportioned 50% of the doses for each radionuclide in the intermediate (V-R) category to the volatile and refractory categories, as discussed above. For example, in calculations at 2 days that assume inhalation of fission products, but no activation products, from fission of U-235 by fission neutrons, doses to the lung were calculated for (1) 26 refractory radionuclides and seven intermediate radionuclides (with individual dose contributions halved as just described), (2) 46 volatile radionuclides and seven intermediate radionuclides (again with halved dose contributions from each of the latter), and (3) all 79 fission products in the unfractionated mixture. The products of these three steps give total doses per fission in the refractory, volatile, and unfractionated categories at the post-detonation times of interest. These three steps were then repeated for each combination of fission mode, yield of uranium activation products, post-detonation (decay) time, target organ or tissue, and exposure pathway of interest.

We then calculated ratios of doses per fission for each exposure and fractionation category to doses per fission for the corresponding exposure categories assuming a complete (i.e., unfractionated) set of radionuclides. We refer to these ratios *unadjusted* fractionation ratios. Using the 2-day example described above to illustrate, the ratio of the dose from refractories to the dose from the unfractionated mixture was calculated by dividing the dose to the lung per fission resulting from inhalation of 26 refractory and seven intermediate fission products by the dose to the lung per fission resulting from inhalation of all 79 fission products in the unfractionated mixture. This step was repeated by dividing the dose to the lung per fission from inhalation of 46 volatile and seven intermediate fission products by the dose to the lung per fission resulting from inhalation of all 79 fission products in the unfractionated mixture.

These calculations are illustrated in the following equations using effective doses that were calculated using equations (1) and (2) as examples:

$$\mathbf{FR_j\ (r{:}u) = \Sigma\ D_{i,j}\ (refractories)/\Sigma\ D_{i,j}\ (unfractionated)} \quad (5)$$

where

$\mathbf{FR_j\ (r{:}u)}$ = unadjusted fractionation ratio for refractory radionuclides for fission mode j,

$\mathbf{\Sigma\ D_{i,j}\ (refractories)}$ = sum of effective doses from intake via inhalation or ingestion of all refractory radionuclides produced in fission mode j (Sv/fission),

$\mathbf{\Sigma\ D_{i,j}\ (unfractionated)}$ = sum of effective doses from intake via inhalation or ingestion of all radionuclides (unfractionated mixture) produced in fission mode j (Sv/fission).

$$\mathbf{FR_j\ (v{:}u) = \Sigma\ D_{i,j}\ (volatiles)/\Sigma\ D_{i,j}\ (unfractionated)} \quad (6)$$

where

$\mathbf{FR_j\ (v{:}u)}$ = unadjusted fractionation ratio for volatile radionuclides for fission mode j,

$\mathbf{\Sigma\ D_{i,j}\ (volatiles)}$ = sum of effective doses from intake via inhalation or ingestion of all volatile radionuclides produced in fission mode j (Sv/fission),

$\mathbf{\Sigma\ D_{i,j}\ (unfractionated)}$ = sum of effective doses from intake via inhalation or ingestion of all radionuclides (unfractionated mixture) produced in fission mode j (Sv/fission).

When uranium activation products are included, the numbers of radionuclides in the refractory grouping and in the unfractionated mixture were increased by two (i.e., to 28 + 7 and 81, respectively).

Paired sets of unadjusted fractionation ratios (ratios of doses per fission from refractories only to doses per fission from unfractionated mixtures and ratios of doses per fission from volatiles only to doses per fission from unfractionated mixtures) were calculated for each combination of fission mode, yield of uranium activation products, post-detonation (decay) time, target organ or tissue, and exposure pathway of interest (see Figure 1). All unadjusted fractionation ratios so obtained are less than unity, because they incorporate an assumption that

all volatiles have been removed from unfractionated fallout without changing the amounts of refractories that would remain, or vice versa.

Because of the way that concentrations of radionuclides in fallout are estimated in dose reconstructions for atomic veterans, the unadjusted fractionation ratios calculated as described above only partially account for the effects of fractionation on doses from internal or external exposure. These ratios must be corrected for the potential effects of fractionation on the levels of external exposure to photons in air above the ground surface.

The need for such a correction is illustrated by the unadjusted fractionation ratios for effective dose rates from external exposure to radionuclides in fallout deposited on the ground given in Table 2. As noted previously, those effective dose rates are a good surrogate for external photon exposure rates in air above the ground surface. Two days after a detonation, results in Table 2 indicate that refractory radionuclides contribute between 36.6 and 61.5% of the total effective dose rate from an unfractionated mixture, depending on the assumed fission mode and assumptions about yields per fission of uranium activation products. The physical basis for this result is that the *average* effective dose rate per radionuclide at 2 days is roughly the same for volatiles and refractories in mixtures of fission products that are present at that time but there are about 60% more volatile fission products than refractories.

In dose reconstructions for atomic veterans, the concentrations of radionuclides in fallout deposited on the ground are estimated on the basis of measured photon exposure rates in air above ground at times within a few days of detonation combined with (1) calculations of the exposure rate in air per unit activity concentration of each radionuclide on the ground surface and (2) estimates of relative activities of radionuclides present in an unfractionated mixture of weapons debris, which are obtained as described in Section 2 (NRC 2003). Thus, if an effective external dose rate at 2 days were due only to refractory radionuclides, calculations based on an assumption of an unfractionated mixture would underestimate the concentrations of refractory radionuclides in deposited fallout by an amount equal to the *reciprocal* of the fractionation ratio derived from effective external dose rates from ground-surface exposure.

We refer to the reciprocal of the fractionation ratio for external effective dose rates from exposure to fallout deposited on the ground as an activity-concentration adjustment factor (ACAF). Values of this factor also are given in Table 2. For example, relative activities of refractories in fallout must be increased by a factor between 1.6 and 2.7 to reproduce the same

external dose rate that results from unfractionated mixtures. Thus, to properly represent the effects of complete fractionation in other dose or dose-rate calculations, including those assuming a 4-year decay period, unadjusted fractionation ratios described above must be increased by the appropriate activity-concentration adjustment factor that describes reductions in external effective dose rates when all volatiles or refractories are removed from unfractionated mixtures on the ground surface. We characterize the corrected sets of fractionation ratios that apply to internal doses or external dose rates to skin as adjusted fractionation ratios (AFRs).

The corrections described above are illustrated for refractories in the following equation, which uses unadjusted fractionation ratios for effective doses per fission resulting from inhalation or ingestion as calculated in equation (5):

$$\mathbf{AFR_j\ (r{:}u) = FR_j\ (r{:}u) \times ACAF_j\ (r{:}u)} \qquad (7)$$

where

$\mathbf{AFR_j\ (r{:}u)}$ = adjusted fractionation ratio for refractory radionuclides for effective doses resulting from inhalation or ingestion of radionuclides produced in fission mode j,

$\mathbf{FR_j\ (r{:}u)}$ = unadjusted fractionation ratio for refractory radionuclides for effective doses resulting from inhalation or ingestion of radionuclides produced in fission mode j [see equation (5)],

$\mathbf{ACAF_j\ (r{:}u)}$ = activity-concentration adjustment factor for refractory radionuclides for fission mode j – i.e., reciprocal of fractionation ratio for refractory radionuclides that applies to effective dose rate from external exposure to radionuclides deposited on ground surface (see Table 2).

Our calculations do not include contributions to doses from unfissioned plutonium in weapons debris, for which all data currently are classified. Plutonium is a potentially important radionuclide in regard to estimating inhalation doses to atomic veterans (NRC 2003). Given that plutonium is one of the most refractory radionuclides in weapons debris (Crocker et al. 1965; Freiling 1961; Freiling et al. 1965), effects of fractionation on doses from plutonium can be bounded by the activity-concentration adjustment factors in Table 2, provided that levels of plutonium in unfractionated weapons debris, as estimated from cloud-sampling data, have been

accurately characterized in carrying out dose reconstructions for atomic veterans. That is, increases in levels of plutonium in fractionated fallout compared with unfractionated weapons debris would not exceed the factor by which concentrations of refractory fission and activation products would need to be increased to give a measured external exposure rate in air that applies to an unfractionated mixture of radionuclides on the ground.

We think that doses or dose rates corrected by activity-concentration adjustment factors (ACAFs), as we have defined them, provide a reasonable representation of the maximal effects of fractionation on doses or dose rates in dose reconstructions for atomic veterans. We reiterate that the fractionation effects of greatest interest to exposures of atomic veterans are those that involve enhancements in abundances of refractory radionuclides relative to volatiles in fallout, i.e., adjusted ratios of doses per fission from refractory radionuclides to doses per fission for the unfractionated mixtures, because participants at the NTS and the Pacific Proving Grounds usually were exposed at locations where fallout was dominated by larger particles that should have contained a higher proportion of refractory radionuclides than unfractionated fallout. An assumption of no fractionation in fallout should result in overestimates of the concentrations of volatile radionuclides deposited on the ground but underestimates of the concentrations of refractory radionuclides. Our calculations that assume complete separation of refractories from volatiles should similarly result in an overestimate of the effects of fractionation, but that was the purpose of our bounding analysis.

4. RESULTS AND DISCUSSION

Results of the calculations described in Section 3.5 are given in Tables 3–12. Adjusted fractionation ratios (AFRs) resulting from calculations of external dose rate to skin and internal dose per fission for the six combinations of radionuclide inventories and decay periods and four fission modes are given in Tables 3–8. Although AFRs for volatile radionuclides are included in Tables 3–8 for completeness, these ratios are not considered germane to an evaluation of effects of fractionation in local fallout to which atomic veterans were primarily exposed. Calculated external dose rates per fission, including the effective dose rate from exposure to fallout on the ground surface, and internal doses per fission for unfractionated mixtures of radionuclides in the same scenarios are given in Tables 9–12. The latter data are useful in examining potential effects of differences in fission mode or yield of activation products on doses to atomic veterans in the absence of fractionation.

Both sets of tables are organized in the same manner. Results for external exposure are presented first, followed by results for effective doses from inhalation or ingestion, and finally by results for doses to individual target organs or tissues from inhalation or ingestion.

4.1 Adjusted Fractionation Ratios for Refractory Radionuclides

AFRs obtained by assuming that only refractory radionuclides are present in fallout [AFR (r:u)] in Tables 3–8 are all less than 2. These results thus suggest that even under extreme assumptions about the extent of fractionation, dose estimates that are obtained by assuming an unfractionated mixture of radionuclides would underestimate the dose to any target organ or tissue from external or internal exposure by less than a factor of two, regardless of fission mode or abundance of activation products, for the two post-detonation decay times we assumed. The average photon energy does not change much from one fission mode to another, and the largest differences in the number of photons per fission among the different fission modes considered occur at ~4–5 days and at 3–5 years (Björnerstedt 1959). The beta/photon intensity ratio peaks at the later times for thermal fission of U-235. If this is also the case for the other fission modes, the range of potential fractionation ratios for fission products at other times may be well characterized by the values at 2 days and 4 years presented in Tables 3–8.

The largest AFR (r:u) of 1.9 was obtained in calculations of dose to the lung at 4 years from inhalation of fission products produced by fission of U-235 by fission neutrons, but with no uranium activation products present (Table 6). That AFR (r:u) is significantly higher than the corresponding values for the other three fission modes because the fission yields for two key longer-lived volatile radionuclides (Ru-106, Sb-125) are significantly lower in the U-235 fission mode, thus reducing the relative contribution to dose from the volatile components of an unfractionated mixture. For all four fission modes, slightly lower AFRs (r:u) of about 1.4–1.7 were obtained in calculations of doses to the lung from inhalation and doses to the colon from ingestion at 2 days, with or without uranium activation products (Table 6). All AFRs (r:u) for doses to the skin at 2 days, with or without uranium activation products, were somewhat lower (1.1–1.7) (Table 3). In all cases, the influence of fission mode on the AFRs (r:u) at 2 days was reduced when uranium activation products were included, because the presence of refractory activation products reduces differences among the doses and dose rates for fractionated and unfractionated materials upon which the AFRs (r:u) are based.

It is also noteworthy that when levels of uranium activation products are increased from the nominal values to 3.3 times those values, the difference between an AFR (r:u) for internal doses and external dose rates to skin and the value 1 typically is reduced. This is as expected because with a sufficiently high content of refractory activation products, the fractional contribution of refractories to the total external dose rate from exposure to photons emitted by unfractionated fallout on the ground surface at 2 days is increased, up to a maximum value of 1. As a result, for external exposure to fallout on the ground, both the activity-concentration adjustment factor (ACAF) defined in Section 3.5 (see also Table 2) and AFR (r:u) approach a value of 1 in the limit, albeit at different rates.[7]

Although the higher level of uranium activation products we assumed in our analysis is strictly applicable only to fallout from detonations of thermonuclear weapons tested in the Pacific, we think it also serves to bound the potential effects that would be obtained by including

[7] This intuitive result appears to be contradicted by results for committed effective doses from inhalation at 2 days for all fission modes given in Table 4 and committed doses to red marrow from ingestion at 2 days for fission of U-235 by a spectrum of fission neutrons or 14-MeV neutrons given in Table 7, which show increasing departures of AFR (r:u) from the value 1 as assumed amounts of uranium activation products are increased from the nominal levels to 3.3 times those levels. In all such cases, however, AFR (r:u) approaches the value 1, as expected, as assumed amounts of uranium activation products are increased still further.

a full suite of short-lived neutron activation products that would occur in weapons debris from detonations at the NTS. Data given by Hicks (1981; 1982) indicate that there are potentially more than twice as many refractory activation products as there are volatile activation products produced by nuclear detonations at the NTS, and that activities of most shorter-lived activation products we did not consider are expected to be lower, typically by several orders of magnitude, than activities of Np-239 and most fission products at 2 days after detonation. Thus, we do not expect that including additional activation products would have a significant effect on our fractionation calculations.

As an additional test of the potential importance of including additional activation products in our calculations, we added what should be conservatively large amounts of soil activation products Co-60 and Eu isotopes with decay-corrected activities relative to the activity of Cs-137 of 15 for Eu-155, 9 for Co-60, 3 for Eu-154, and 3 for Eu-152, as derived from soil survey data at the NTS (McArthur and Mead 1987), to the refractory radionuclides in a mixture of fission products at 4 years. In this extremely unlikely case, all values of AFR (r:u) were $\leq$1 and all values that were <1 without soil activation products increased when soil activation products were included. Although these calculations could be revisited with more realistic relative activities of fission and activation products, these results, along with those for cases where uranium activation products were included in calculations at 2 days, appear to reinforce the idea that the potential effects of activation scenarios on fractionation at times $\geq$2 days probably have been bounded by our calculations.

In many calculations of internal doses from ingestion or inhalation at 4 years after detonation, the results indicate that doses to some organs and tissues that would be obtained by assuming an unfractionated mixture of radionuclides could overestimate actual doses by more than two orders of magnitude if significant fractionation (i.e., enhancement of refractories) occurred. For example, values of AFR (r:u) for red marrow and pancreas at 4 years in Tables 7 and 8 are about 0.1 or less. In these cases, the principal contributors to internal dose from exposure to unfractionated fallout are the volatile radionuclides Sr-90, Ru-106, and Cs-137. It also is important to bear in mind, however, that internal doses from exposure to fission products at 4 years usually should be low and often would be insignificant compared with internal doses from exposure to plutonium (NRC 2003).

4.2 Doses from Unfractionated Mixtures of Fission and Uranium Activation Products

In this section, we examine the potential effects of differences in fission mode or yield of activation products on doses to atomic veterans in the absence of fractionation. Comparisons of doses per fission for unfractionated mixtures given in Tables 9-12 indicate that the largest differences produced by variations in radionuclide content among the four fission modes are of the same order of magnitude as the differences in the adjusted fractionation ratios [AFRs (r:u)] in Tables 3-8 for a given decay time (i.e., about a factor of 2). However, in most cases, the effects of differences in fission mode on doses per fission typically are much less than the effects on AFRs (r:u) (i.e., $\leq$20%). The largest effects of differences in fission mode on doses are seen at 4 years (Tables 9-12). The effective dose from inhalation of fission products produced by fission of Pu-239 is 1.5 times that for U-235 fission at 4 years, while nearly the reverse is true for ingestion, where the effective dose from U-235 fission products is 1.2 times that from Pu-239 fission (Table 10). These comparisons hold regardless of whether calculations are based on dose coefficients for the public or workers, and the relatively small differences observed between the two sets of calculations indicate that distinctions between workers and members of the public are not needed. Dose coefficients for workers probably are more appropriate for exposures at the NTS, but this may not be the case in the Pacific, where many participants were exposed during off-duty activities.

A larger difference (1.8 times) is observed when comparing the effective dose from external exposure at 4 years from U-238 fission by high-energy neutrons with that from U-235 fission by fission neutrons (Table 9). The former is expected to be the dominant fission mode in thermonuclear weapons tested in the Pacific (Freiling et al. 1965), whereas fission of U-235 (and Pu-239) by fission neutrons should be the dominant contributors to yields of nuclear weapons tested at the NTS. Fission of U-238 by high-energy neutrons should not have occurred in weapons tested at the NTS, although a small contribution from fission of U-238 by fission neutrons would be expected. Thus, the observed difference of a factor of 1.8 noted above may not be particularly meaningful because contributions from those two fission modes should dominate spectra of fission products produced in weapons tests under radically different conditions. That is, uncertainties in doses resulting from uncertainties in activities contributed by one fission mode should not contribute to uncertainties in doses produced by tests in which the

other mode was dominant. This is unlike the situation with some tests of fission weapons at the NTS, in which contributions to activities of fission products from several fission modes (such as U-235 and Pu-239 fission—and potentially U-238 fission—by fission neutrons) was possible.

More meaningful differences in doses per fission due to differences in activities of fission products generated in different fission modes are found in calculated doses to individual organs or tissues from inhalation or ingestion of fission products alone at 4 years after detonation. As indicated in Table 11, for example, the dose to the lung from inhalation of unfractionated fission products produced by fission of Pu-239 is 1.9 times that for U-235 fission, while the dose to the colon from ingestion of Pu-239 fission products is 1.3 times that from U-235 fission. This pattern is somewhat different from what was seen in the comparisons of effective doses from inhalation or ingestion of fission products produced by these two fission modes, where the effective dose to the lung from Pu-239 fission was 1.5 times that for U-235 fission and the dose to the colon from U-235 fission was 1.2 times larger than that from Pu-239 fission. The higher dose contributions to lung and colon from inhaled or ingested Pu-239 fission products are linked to the higher fission yield of Ru-106 in this mode. The yield of Ru-106 in Pu-239 fission is more than eight times the yield in U-235 fission by fission neutrons, and Ru-106 contributes about 70% of the total dose to the lung from inhalation and about 50% of the total dose to the colon from ingestion of unfractionated mixtures of Pu-239 fission products in our scenarios.

In another case for which doses per fission are given in Table 12, doses to red marrow at 4 years from inhalation or ingestion of radionuclides in unfractionated mixtures of fission products produced by fission of U-235 by fission neutrons are 2.3–2.4 times greater than those produced by fission of Pu-239. This difference is due primarily to the higher yield of Sr-90 in U-235 fission (2.7 times greater than the yield in Pu-239 fission). Although yields of Cs-137, Ce-144, and Pm-147 also are higher in U-235 fission, these increases serve primarily to offset the contributions to dose from Ru-106, Sb-125, and Eu-155, which have higher yields in Pu-239 fission.

5. SUMMARY AND CONCLUSIONS

Our bounding analysis of potential effects of fractionation of radionuclides in fallout on reconstructed doses to atomic veterans indicates that, if unfissioned plutonium is excluded, neglect of fractionation could result in underestimates of dose, but that the extent of underestimation probably is less than a factor of two even under the most extreme (and highly unlikely) assumption that fallout contains only refractory fission and activation products. In many cases, however, the current approach of neglecting fractionation in dose reconstructions for atomic veterans probably results in overestimates of doses from exposure to fission and activation products if significant fractionation (i.e., enhancement of refractory radionuclides relative to volatiles) occurred.

The conclusions summarized above do not take into account potential effects of contributions from unfissioned plutonium in weapons debris, for which all data are classified and, thus, have not been included in our calculations. However, the effects of fractionation on doses from plutonium should be bounded by the activity-concentration adjustment factors derived from an analysis of effects of fractionation on effective dose rates from exposure to radionuclides on the ground given in Table 2, provided that levels of plutonium in unfractionated weapons debris have been accurately characterized on the basis of cloud-sampling data in carrying out dose reconstructions for atomic veterans. Under that condition, doses from plutonium would be underestimated by less than a factor of three in calculations that assume no fractionation even if fallout contained refractory radionuclides only.

There are at least two reasons why our bounding analysis has likely captured the potential effects of fractionation on doses to atomic veterans from exposure to fission and activation products. An obvious reason is that complete separation of refractories from volatiles in fallout has never been reported. The other is that many radionuclides, including Sr-90 and Np-239, that figure prominently in the results described in the preceding section do not exhibit the “black or white” volatility behavior that we and Hicks (1982) have attributed to them (e.g., see Crocker et al. 1965; Freiling et al. 1965; Prokofiev and Smirnov 2000). Rather, these radionuclides, along with others that we have classified as either volatile (e.g., Ru-103) or refractory (e.g., Te-132), have been shown to exhibit intermediate fractionation behavior. Factoring in such behavior

would effectively blur the distinctions between the volatile and refractory categories and reduce differences in doses between them.

We were only able to find published data on fractionation behavior for less than 20% of the 79 radionuclides we included in our calculations. Thus, more exact quantitative comparisons of doses from exposures to fractionated and unfractionated fallout probably are impractical and bounding calculations or related mathematical exercises akin to those we performed are the most reasonable approach. Although modeling of fractionation behavior in mass chains produced in nuclear detonations and neutron activation of weapons and soil components based on first principles could be attempted, i.e., by using available information on decay modes, neutron fluxes and capture cross sections of precursors of activation products, volatilities of precursor nuclides, thermal-temporal characteristics of fireballs, and the nature of environmental or other materials incorporated into the fireballs or exposed to neutron fluxes, it seems doubtful that such an approach would be useful, given the large number of variables in such calculations, the limited shot-specific data from nuclear weapons testing available to assess the accuracy of model predictions, and indications from these limited data that there is a large, sometimes unpredictable, test-to-test variability in fallout characteristics. Results from our analysis, which indicate that doses to atomic veterans could be underestimated by less than a factor of two in the worst cases, also argue against the usefulness of a more rigorous analysis of effects of fractionation.

Our analysis clearly indicates that the potential degree of underestimation of external and internal doses to atomic veterans that results from neglect of fractionation in all dose reconstructions is not large – i.e., less than a factor of two for external and internal exposure to fission and activation products and less than a factor of three for internal exposure to plutonium. Therefore, given the conservative assumptions that often are incorporated in dose reconstructions (NRC, 2003), potential underestimations of dose probably are less than values of simple adjustment factors specified in the 2003 Interim Guidance (Benavides 2003) that are applied to estimates of dose from specific pathways to obtain upper bounds (i.e., at least upper 95% credibility limits). That is, it is unlikely that additional adjustments to account for effects of fractionation would be needed to obtain credible upper bounds of dose to atomic veterans.

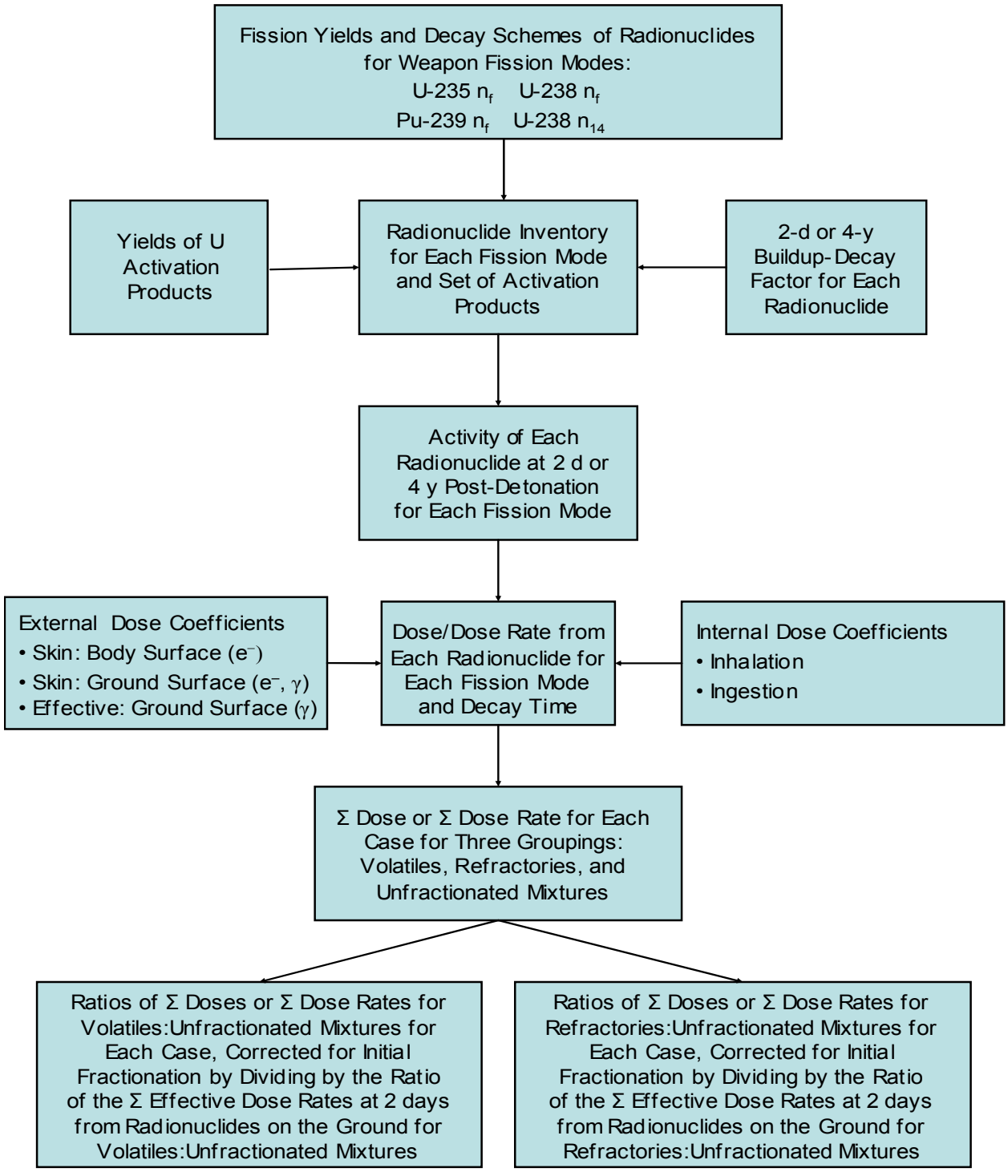

Figure 1. Summary of Approach to Bounding Analysis of Effects of Radionuclide Fractionation on Estimates of Dose from Different Exposure Pathways

Table 1. Fission and activation product radionuclides included in analysis[a]

Fission products

Ge-77	Zr-97	Ag-111	Sb-127	I-135	**Pm-147**
As-77	Nb-97m	Pd-112	**Te-127m**	Cs-136	Pm-149
Sr-89	Nb-97	Ag-112	**Te-127**	**Cs-137**	Pm-151
Sr-90	Mo-99	Ag-113	Sb-128	**Ba-137m**	Sm-153
Y-90	Tc-99m	**Cd-113m**	Sb-129	Ba-140	**Eu-155**
Sr-91	**Ru-103**	**Cd-115m**	**Te-129m**	La-140	Sm-156
Y-91m	**Rh-103m**	Cd-115	**Te-129**	La-141	Eu-156
Y-91	Ru-105	In-115m	I-130	**Ce-141**	Eu-157
Sr-92	Rh-105m	Sn-121	Te-131m	Ce-143	Gd-159
Y-92	Rh-105	**Sn-123**	Te-131	Pr-143	
Y-93	**Ru-106**	Sn-125	I-131	**Ce-144**	
Zr-95	**Rh-106**	**Sb-125**	Te-132	**Pr-144**	
Nb-95m	Pd-109	**Te-125m**	I-132	Pr-145	
Nb-95	Ag-109m	Sb-126	I-133	Nd-147	

Activation products

U-237	Np-239

[a]All radionuclides were included in dose calculations at 2 days after detonation; radionuclides highlighted in bold were included in calculations at 4 years.

Table 2. Fractionation ratios for external effective dose rates from exposure to radionuclides on ground surface for four fission modes and two activation scenarios at 2 days after detonation[a]

Radionuclides	Fractionation ratio for volatiles[b]				Fractionation ratio for refractories[c]			
	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
Fission products only	0.57	0.63	0.60	0.62	0.43	0.37	0.40	0.38
Fission products + uranium activation products	0.50	0.56	0.53	0.54	0.50	0.45	0.48	0.46
Fission products + uranium activation products increased by a factor of 3.3	0.39	0.43	0.41	0.42	0.62	0.57	0.60	0.58
	Reciprocals of the fractionation ratios (activity-concentration adjustment factors)							
Fission products only	1.8	1.6	1.7	1.6	2.3	2.7	2.5	2.7
Fission products + uranium activation products	2.0	1.8	1.9	1.9	2.0	2.2	2.1	2.2
Fission products + uranium activation products increased by a factor of 3.3	2.6	2.4	2.5	2.4	1.6	1.7	1.7	1.7

[a]Fractionation ratios are calculated by assuming complete separation of volatile and refractory components.
[b]Ratio of dose rate from volatile radionuclides only to dose rate from unfractionated mixture.
[c]Ratio of dose rate from refractory radionuclides only to dose rate from unfractionated mixture.

Table 3. Adjusted fractionation ratios for external dose rates to skin from exposure to radionuclides produced in four fission modes as a function of decay time, exposure pathway, and assumed yields of activation products

Radionuclides (decay time)	Exposure pathway	Volatiles:Unfractionated (v:u)				Refractories:Unfractionated (r:u)			
		U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
Fission products (2 d)	Deposition on skin	0.72	0.80	0.75	0.83	1.4	1.4	1.4	1.3
Fission products + U (2 d)	Deposition on skin	0.51	0.57	0.53	0.60	1.5	1.5	1.5	1.5
Fission products + 3.3 × U (2 d)	Deposition on skin	0.35	0.39	0.37	0.42	1.4	1.5	1.4	1.4
Fission products (4 y)	Deposition on skin	1.0	1.1	0.99	1.1	0.98	0.87	1.0	0.86
Fission products + U (4 y)	Deposition on skin	1.2	1.2	1.1	1.3	0.84	0.72	0.86	0.71
Fission products + 3.3 × U (4 y)	Deposition on skin	1.5	1.6	1.5	1.6	0.69	0.56	0.68	0.56
Fission products (2 d)	Deposition on ground	0.58	0.62	0.59	0.67	1.6	1.7	1.6	1.6
Fission products + U (2 d)	Deposition on ground	0.64	0.68	0.65	0.75	1.4	1.4	1.4	1.3
Fission products + 3.3 × U (2 d)	Deposition on ground	0.78	0.82	0.79	0.91	1.1	1.1	1.1	1.1
Fission products (4 y)	Deposition on ground	0.91	1.2	1.1	1.1	1.1	0.69	0.92	0.84
Fission products + U (4 y)	Deposition on ground	1.1	1.3	1.2	1.3	0.95	0.57	0.77	0.70
Fission products + 3.3 × U (4 y)	Deposition on ground	1.4	1.7	1.6	1.7	0.78	0.45	0.61	0.55

Table 4. Adjusted fractionation ratios for 50-y committed effective doses from inhalation of radionuclides produced in four fission modes as a function of decay time, dose-coefficient selection, and assumed yields of activation products

		Volatiles:Unfractionated (v:u)				Refractories:Unfractionated (r:u)			
Radionuclides	Decay time	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
		Values based on dose coefficients for the public							
Fission products	2 d	0.93	0.99	0.96	1.0	1.1	1.0	1.1	0.99
Fission products + U	2 d	0.71	0.76	0.72	0.78	1.3	1.3	1.3	1.3
Fission products + 3.3 × U	2 d	0.51	0.56	0.52	0.57	1.3	1.3	1.3	1.3
Fission products	4 y	0.69	1.1	0.94	1.0	1.4	0.79	1.1	0.98
Fission products + U	4 y	0.79	1.3	1.1	1.2	1.2	0.65	0.91	0.81
Fission products + 3.3 × U	4 y	1.0	1.7	1.4	1.5	0.99	0.51	0.73	0.63
		Values based on dose coefficients for workers							
Fission products	2 d	0.95	1.0	0.97	1.0	1.1	1.0	1.0	0.97
Fission products + U	2 d	0.73	0.78	0.75	0.80	1.3	1.3	1.3	1.2
Fission products + 3.3 × U	2 d	0.54	0.58	0.55	0.60	1.3	1.3	1.3	1.3
Fission products	4 y	0.72	1.1	0.96	1.0	1.4	0.78	1.1	0.96
Fission products + U	4 y	0.82	1.3	1.1	1.2	1.2	0.64	0.90	0.79
Fission products + 3.3 × U	4 y	1.1	1.7	1.4	1.5	0.96	0.50	0.71	0.62

Table 5. Adjusted fractionation ratios for 50-y committed effective doses from ingestion of radionuclides produced in four fission modes as a function of decay time, dose-coefficient selection, and assumed yields of activation products

Radionuclides	Decay time	Volatiles:Unfractionated (v:u)				Refractories:Unfractionated (r:u)			
		U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
		Values based on dose coefficients for the public							
Fission products	2 d	1.3	1.2	1.2	1.2	0.66	0.63	0.65	0.61
Fission products + U	2 d	1.2	1.2	1.2	1.2	0.80	0.80	0.81	0.78
Fission products + 3.3 × U	2 d	1.1	1.1	1.1	1.1	0.93	0.93	0.94	0.91
Fission products	4 y	1.5	1.4	1.5	1.4	0.28	0.29	0.32	0.29
Fission products + U	4 y	1.8	1.6	1.7	1.6	0.24	0.24	0.27	0.24
Fission products + 3.3 × U	4 y	2.3	2.1	2.2	2.1	0.19	0.19	0.21	0.19
		Values based on dose coefficients for workers							
Fission products	2 d	1.3	1.2	1.2	1.2	0.67	0.64	0.67	0.62
Fission products + U	2 d	1.3	1.2	1.2	1.2	0.73	0.75	0.75	0.73
Fission products + 3.3 × U	2 d	1.1	1.1	1.1	1.1	0.94	0.94	0.94	0.92
Fission products	4 y	1.5	1.4	1.5	1.4	0.28	0.29	0.32	0.29
Fission products + U	4 y	1.8	1.6	1.7	1.6	0.24	0.24	0.27	0.24
Fission products + 3.3 × U	4 y	2.3	2.1	2.2	2.1	0.19	0.19	0.21	0.19

Table 6. Adjusted fractionation ratios for 50-y committed doses to lung from inhalation and colon from ingestion by workers of radionuclides produced in four fission modes as a function of decay time and assumed yields of activation products

Radionuclides (decay time)	Target organ	Volatiles:Unfractionated (v:u)				Refractories:Unfractionated (r:u)			
		U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
	Exposure via inhalation								
Fission products (2 d)	Lung	0.53	0.72	0.62	0.73	1.6	1.5	1.6	1.4
Fission products + U (2 d)	Lung	0.32	0.45	0.37	0.46	1.7	1.7	1.7	1.7
Fission products + 3.3 × U (2 d)	Lung	0.20	0.28	0.23	0.29	1.5	1.5	1.5	1.5
Fission products (4 y)	Lung	0.33	1.1	0.85	0.93	1.9	0.84	1.2	1.1
Fission products + U (4 y)	Lung	0.38	1.3	0.97	1.1	1.6	0.69	1.0	0.92
Fission products + 3.3 × U (4 y)	Lung	0.49	1.6	1.3	1.4	1.3	0.54	0.82	0.72
	Exposure via ingestion								
Fission products (2 d)	Colon	0.54	0.63	0.57	0.69	1.6	1.7	1.6	1.6
Fission products + U (2 d)	Colon	0.40	0.46	0.42	0.51	1.6	1.7	1.6	1.6
Fission products + 3.3 × U (2 d)	Colon	0.29	0.32	0.30	0.37	1.5	1.5	1.5	1.5
Fission products (4 y)	Colon	0.95	1.2	1.1	1.1	1.1	0.71	0.92	0.83
Fission products + U (4 y)	Colon	1.1	1.3	1.2	1.3	0.91	0.58	0.77	0.68
Fission products + 3.3 × U (4 y)	Colon	1.4	1.7	1.6	1.7	0.75	0.45	0.61	0.54

Table 7. Adjusted fractionation ratios for 50-y committed doses to red marrow from inhalation or ingestion by workers of radionuclides produced in four fission modes as a function of decay time and assumed yields of activation products

Radionuclides	Decay time	Volatiles:Unfractionated (v:u)				Refractories:Unfractionated (r:u)			
		U-235 n_f	Pu-239 n_f	U-238 n_f	**U-238 n_{14}**	U-235 n_f	Pu-239 n_f	U-238 n_f	**U-238 n_{14}**
		Exposure via inhalation							
Fission products	2 d	1.0	0.92	0.98	0.99	0.96	1.1	1.0	1.0
Fission products + U	2 d	1.0	0.90	0.96	0.98	0.96	1.1	1.0	1.0
Fission products + 3.3 × U	2 d	1.1	0.88	0.94	0.98	0.96	1.1	1.0	1.0
Fission products	4 y	1.7	1.5	1.6	1.6	0.029	0.11	0.066	0.064
Fission products + U	4 y	2.0	1.7	1.9	1.8	0.025	0.090	0.055	0.052
Fission products + 3.3 × U	4 y	2.6	2.2	2.4	2.3	0.020	0.070	0.044	0.041
		Exposure via ingestion							
Fission products	2 d	0.99	0.88	0.90	0.95	1.0	1.2	1.2	1.1
Fission products + U	2 d	1.1	0.92	0.95	1.0	0.95	1.1	1.1	1.0
Fission products + 3.3 × U	2 d	1.2	1.0	1.0	1.1	0.91	1.0	0.97	0.93
Fission products	4 y	1.8	1.6	1.7	1.6	0.0032	0.0067	0.0053	0.0047
Fission products + U	4 y	2.0	1.8	1.9	1.8	0.0028	0.0055	0.0045	0.0039
Fission products + 3.3 × U	4 y	2.6	2.3	2.5	2.4	0.0023	0.0043	0.0036	0.0030

Table 8. Adjusted fractionation ratios for 50-y committed doses to pancreas from inhalation or ingestion by workers of radionuclides produced in four fission modes as a function of decay time and assumed yields of activation products

Radionuclides	Decay time	Volatiles:Unfractionated (v:u)				Refractories:Unfractionated (r:u)			
		U-235 n_f	Pu-239 n_f	U-238 n_f	**U-238 n_{14}**	U-235 n_f	Pu-239 n_f	U-238 n_f	**U-238 n_{14}**
		Exposure via inhalation							
Fission products	2 d	0.78	0.79	0.72	0.77	1.3	1.4	1.4	1.4
Fission products + U	2 d	0.79	0.80	0.73	0.79	1.2	1.3	1.3	1.3
Fission products + 3.3 × U	2 d	0.80	0.82	0.76	0.82	1.1	1.1	1.2	1.1
Fission products	4 y	1.7	1.5	1.6	1.5	0.092	0.12	0.12	0.11
Fission products + U	4 y	1.9	1.7	1.8	1.8	0.079	0.095	0.098	0.090
Fission products + 3.3 × U	4 y	2.5	2.2	2.4	2.3	0.064	0.074	0.078	0.071
		Exposure via ingestion							
Fission products	2 d	0.91	0.91	0.89	0.91	1.1	1.2	1.2	1.2
Fission products + U	2 d	0.94	0.94	0.92	0.94	1.1	1.1	1.1	1.1
Fission products + 3.3 × U	2 d	0.99	1.0	0.98	1.0	1.0	1.0	1.0	1.0
Fission products	4 y	1.8	1.6	1.7	1.6	0.0031	0.0025	0.0030	0.0030
Fission products + U	4 y	2.0	1.8	1.9	1.8	0.0027	0.0021	0.0026	0.0025
Fission products + 3.3 × U	4 y	2.6	2.3	2.5	2.4	0.0022	0.0016	0.0020	0.0020

Table 9. External dose rates (Sv/h) per fission from unfractionated mixtures of radionuclides produced in four fission modes as a function of decay time, target organ, exposure pathway, and assumed yields of activation products

Radionuclides (decay time)	Target organ	Fission mode			
		U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
	Exposure to radionuclides deposited on skin				
Fission products (2 d)	Skin	2.0E-12	2.1E-12	2.0E-12	2.1E-12
Fission products + U (2 d)	Skin	3.2E-12	3.3E-12	3.2E-12	3.3E-12
Fission products + 3.3 × U (2 d)	Skin	6.1E-12	6.1E-12	6.1E-12	6.2E-12
Fission products (4 y)	Skin	4.5E-16	4.5E-16	4.4E-16	4.5E-16
	Exposure to radionuclides deposited on ground surface				
Fission products (2 d)	Skin	1.8E-13	1.7E-13	1.7E-13	1.8E-13
Fission products + U (2 d)	Skin	1.9E-13	1.7E-13	1.8E-13	1.8E-13
Fission products + 3.3 × U (2 d)	Skin	2.0E-13	1.8E-13	1.9E-13	1.9E-13
Fission products (4 y)	Skin	4.1E-17	5.3E-17	4.6E-17	4.3E-17
	Exposure to radionuclides deposited on ground surface				
Fission products (2 d)	Effective dose	2.2E-14	2.3E-14	2.2E-14	2.2E-14
Fission products + U (2 d)	Effective dose	2.6E-14	2.6E-14	2.6E-14	2.5E-14
Fission products + 3.3 × U (2 d)	Effective dose	3.3E-14	3.3E-14	3.3E-14	3.3E-14
Fission products (4 y)	Effective dose	1.0E-18	1.6E-18	1.2E-18	1.9E-18

Table 10. 50-year committed effective doses (Sv) per fission from internal exposure to unfractionated mixtures of radionuclides produced in four fission modes as a function of decay time, exposure pathway, dose-coefficient selection, and assumed yields of activation products

		Inhalation				Ingestion			
Radionuclides	Decay time	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
		Values based on dose coefficients for the public							
Fission products	2 d	1.3E-15	1.4E-15	1.3E-15	1.4E-15	2.3E-15	2.4E-15	2.3E-15	2.3E-15
Fission products + U	2 d	2.0E-15	2.1E-15	2.0E-15	2.1E-15	2.7E-15	2.8E-15	2.7E-15	2.8E-15
Fission products + 3.3 × U	2 d	3.6E-15	3.7E-15	3.6E-15	3.7E-15	3.8E-15	3.9E-15	3.8E-15	3.9E-15
Fission products	4 y	4.2E-18	6.5E-18	5.4E-18	5.2E-18	2.0E-18	1.6E-18	1.7E-18	1.6E-18
		Values based on dose coefficients for workers							
Fission products	2 d	1.3E-15	1.4E-15	1.3E-15	1.4E-15	2.3E-15	2.4E-15	2.3E-15	2.4E-15
Fission products + U	2 d	2.0E-15	2.0E-15	2.0E-15	2.0E-15	2.7E-15	2.8E-15	2.7E-15	2.8E-15
Fission products + 3.3 × U	2 d	3.5E-15	3.6E-15	3.5E-15	3.5E-15	3.8E-15	3.9E-15	3.8E-15	3.9E-15
Fission products	4 y	4.0E-18	6.1E-18	5.1E-18	4.9E-18	2.0E-18	1.6E-18	1.7E-18	1.6E-18

Table 11. 50-year committed doses (Sv) per fission to lung from inhalation and colon from ingestion by workers of unfractionated mixtures of radionuclides produced in four fission modes as a function of decay time, target organ, and assumed yields of activation products

Radionuclides (decay time)	Target organ	Fission mode			
		U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
	Exposure via inhalation				
Fission products (2 d)	Lung	5.0E-15	5.3E-15	5.0E-15	5.2E-15
Fission products + U (2 d)	Lung	9.4E-15	9.7E-15	9.4E-15	9.7E-15
Fission products + 3.3 × U (2 d)	Lung	2.0E-14	2.0E-14	2.0E-14	2.0E-14
Fission products (4 y)	Lung	2.3E-17	4.5E-17	3.5E-17	3.3E-17
	Exposure via ingestion				
Fission products (2 d)	Colon	6.3E-15	6.1E-15	6.1E-15	6.3E-15
Fission products + U (2 d)	Colon	9.7E-15	9.5E-15	9.5E-15	9.8E-15
Fission products + 3.3 × U (2 d)	Colon	1.8E-14	1.8E-14	1.7E-14	1.8E-14
Fission products (4 y)	Colon	4.2E-18	5.3E-18	4.6E-18	4.5E-18

Table 12. 50-year committed doses (Sv/fission) to red marrow and pancreas from inhalation or ingestion by workers of unfractionated mixtures of radionuclides produced in four fission modes as a function of decay time and assumed yields of activation products

Radionuclides	Decay time	Red marrow				Pancreas			
		U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}	U-235 n_f	Pu-239 n_f	U-238 n_f	U-238 n_{14}
		Exposure via inhalation							
Fission products	2 d	1.7E-16	1.3E-16	1.4E-16	1.5E-16	6.8E-17	7.4E-17	7.7E-17	7.6E-17
Fission products + U	2 d	2.0E-16	1.6E-16	1.6E-16	1.7E-16	7.7E-17	8.3E-17	8.7E-17	8.5E-17
Fission products + 3.3 × U	2 d	2.5E-16	2.1E-16	2.1E-16	2.2E-16	9.9E-17	1.0E-16	1.1E-16	1.1E-16
Fission products	4 y	6.4E-18	2.7E-18	4.0E-18	3.9E-18	2.5E-19	3.2E-19	2.7E-19	2.8E-19
		Exposure via ingestion							
Fission products	2 d	2.1E-16	1.9E-16	1.9E-16	2.0E-16	1.1E-16	1.1E-16	1.1E-16	1.1E-16
Fission products + U	2 d	2.2E-16	2.1E-16	2.1E-16	2.1E-16	1.2E-16	1.3E-16	1.2E-16	1.2E-16
Fission products + 3.3 × U	2 d	2.6E-16	2.5E-16	2.5E-16	2.5E-16	1.4E-16	1.5E-16	1.5E-16	1.5E-16
Fission products	4 y	7.4E-18	3.3E-18	4.7E-18	4.6E-18	6.2E-19	7.2E-19	6.3E-19	5.7E-19

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APPENDIX A . PARAMETERS AND DOSE COEFFICIENTS FOR RADIONUCLIDES USED IN CALCULATIONS

Table A.1. Half-lives, chemical characteristics, and decay relationships for radionuclides used in calculating activity at different times after detonation

Nuclide	Half-life	Volatile (V) or Refractory (R)[a]	Specific activity (Bq/atom)	2-day buildup-decay factor (branching ratio)	4-year buildup-decay factor
Ge-77	11.3 h	V	1.70E-05	5.27E-02	
As-77	38.8 h	V	4.96E-06	4.24E-01[n,o]	
Sr-89	50.55 d	V	1.59E-07[b]	2.06E-04[n]	1.99E-09
Sr-90	28.6 y	V	7.68E-10	1.00E+00	9.08E-01
Y-90	64.1h	V		4.05E-01[n]	1.00E+00[n]
Sr-91	9.5 h	V-R	2.03E-05	3.02E-02	0.00E+00
Y-91m	49.71 m	V-R		1.10E+00[n] (0.574)	
Y-91	58.51 d	V-R		2.14E-01[n]	3.09E-08[x]
Sr-92	2.71 h	R	7.10E-05	4.67E-06	
Y-92	3.54 h	R		5.48E+01[n]	
Y-93	10.1 h	R	1.91E-05	3.71E-02	
Zr-95	64.02 d	R	1.25E-07	9.80E-01	1.37E-07
Nb-95m	86.6 h	R		3.10E-01[n] (0.0078)	1.06E+00[n]
Nb-95	35.06 d	R		3.74E-02[n,p] (0.9922)	2.21E+00[n,y]
Zr-97	16.9 h	R	1.14E-05	1.40E-01	
Nb-97m	60 s	R		1.00E+00[n] (0.947)	
Nb-97	1.20 h	R		1.08E+00[n] (0.0053)	
Mo-99	66.02 h	R	2.92E-06	6.04E-01	
Tc-99m	6.02 h	R		1.09E+00[n] (0.886)	
Ru-103	39.35 d	V	2.04E-07	9.65E-01	6.81E-12
Rh-103m	56.119 m	V		1.00E+00[n] (0.997)	1.00E+00
Ru-105	4.44 h	V	4.34E-05	5.58E-04	
Rh-105m	45 s	V		1.00E+00[n] (0.245)	
Rh-105	35.36 h	V		1.00E+02[n]	
Ru-106	368.2 d	V	2.18E-08	9.96E-01	6.41E-02
Rh-106	29.92 s	V		1.00E+00[n]	1.00E+00
Pd-109	13.53 h	V	1.42E-05	8.56E-02	
Ag-109m	39.6 s	V		1.00E+00[n] (0.99949)	
Ag-111	7.46 d	V	5.02E-04[c]	1.78E-03[n]	
Pd-112	20.04 h	V	9.61E-06	1.90E-01	
Ag-112	3.13 h	V		1.18E+00[n]	
Ag-113	5.3h	V	3.63E-05	1.88E-03	
Cd-113m	13.7 y	V	1.60E-09	1.00E+00	8.17E-01
Cd-115m	44.6 d	V	1.80E-07[d]	3.17E-04[n]	1.41E-10

Table A.1 (continued)

Nuclide	Half-life	Volatile (V) or Refractory (R)[a]	Specific activity (Bq/atom)	2-day buildup-decay factor (branching ratio)	4-year buildup-decay factor
Cd-115	53.46 h	V		3.54E-03[n]	
In-115m	4.36 h	V		3.85E-03[n]	
Sn-121	1.128 d	V	7.11E-06	2.93E-01	
Sn-123	129.2 d	V	6.21E-08	9.89E-01	3.97E-04
Sn-125	9.64 d	V	8.32E-07	8.66E-01	2.62E-46
Sb-125	2.77 y	V	7.93E-09	9.99E-01[n,q]	3.68E-01
Te-125m	58 d	V		2.36E-02[n,q] (0.231)	1.06E+00[n]
Sb-126	12.4 d	V	6.08E-04[e]	9.52E-04[n]	
Sb-127	3.85 d	V	2.08E-06[f]	1.23E-05[n]	7.37E-115
Te-127	9.35 h	V		1.71E-02[n,s] (0.831)	1.11E+00[n,s]
Te-127m	109 d	V		2.28E-04[n] (0.169)	4.62E+108[n]
Sb-128	9.1 h	V	2.12E-05	2.59E-02	
Sb-129	4.40 h	V	4.38E-05	5.21E-04	0.00E+00
Te-129	69.6 m	V		1.36E+00[n,t] (0.834)	1.36E+00[n,t]
Te-129m	33.6 d	V	2.39E-07	1.01E+01[n] (0.166)	8.36E-14[z]
I-130	12.36 h	V	1.56E-05	6.78E-02	
Sb-131	23 m	V	5.02E-04		
Te-131m	30 h	V	6.42E-06	3.30E-01[n,u]	
Te-131	25.0 m	V	4.62E-04	2.15E-35[n,v]	
I-131	8.04 d	V	9.98E-07	w	
Te-132	78.2 h	V	2.46E-06	6.54E-01	
I-132	2.30 h	V		1.00E+00[n]	
I-133	20.8 h	V	2.08E-04[g]	9.39E-03	
I-135	6.61 h	V	2.91E-05	6.52E-03	
Cs-136	13.16 d	V	6.09E-07	9.00E-01	
Cs-137	30.17 y	V	7.28E-10	1.00E+00	9.12E-01
Ba-137m	2.522 m	V		9.46E-01[n]	9.46E-01[n]
Ba-140	12.789 d	V-R	6.27E-07	8.97E-01	
La-140	40.22 h	V-R		5.90E-01[n]	
La-141	3.94 h	V-R	4.89E-05[h]	1.80E-05	0.00E+00
Ce-141	32.50 d	V-R		3.76E-04[h,n]	3.02E-14[h,n]
Ce-143	33.0 h	R	6.42E-04[i]	3.35E-03	
Pr-143	13.56 d	R		5.49E-04[i,n]	
Ce-144	284.3 d	R	2.82E-08	9.95E-01	2.85E-02
Pr-144	17.14 m	R		1.00E+00[n]	1.00E+00[n]
Pr-145	5.98 h	R	3.22E-05	3.84E-03	
Nd-147	10.98 d	R	7.30E-07[j]	6.69E-04	9.57E-41
Pm-147	2.6234 y	R		1.03E-06[n]	4.21E+37[n]

Table A.1 (continued)

Nuclide	Half-life	Volatile (V) or Refractory (R)[a]	Specific activity (Bq/atom)	2-day buildup-decay factor (branching ratio)	4-year buildup-decay factor
Pm-149	53.08 h	R	1.11E-04[k]	1.80E-02[n]	
Pm-151	28.4 h	R	8.89E-04[l]	2.38E-03[n]	
Sm-153	46.7 h	R	4.12E-06	4.91E-01	
Eu-155	4.96 y	R	4.43E-09	1.00E+00	5.72E-01
Sm-156	9.4 h	R	2.05E-05	2.91E-02	
Eu-156	15.19 d	R	5.28E-07	8.05E-01	
Eu-157	15.13 h	R	1.27E-05	1.11E-01	
Gd-159	18.6 h	R	1.03E-05	1.67E-01	
U-237	6.75 d	R	1.19E-06	8.14E-01	
Np-239	2.355 d	R	4.94E-04[m]	2.91E-03[n]	

[a]V-R = radionuclides with volatility intermediate between that of volatiles and refractories.

[b]Specific activity of 15.4-min Rb-89 precursor (7.50E-04 Bq/atom) is used in 2-day calculations.

[c]Specific activity of 23-min Pd-111 precursor used in calculations.

[d]Specific activity of 21-min Ag-115 precursor (5.50E-04 Bq/atom) is used in 2-day calculations for Cd-115m, Cd-115, and In-115m.

[e]Specific activity of 19-min Sb-126m precursor used in calculations.

[f]Specific activity of 2.1-h Sn-127 precursor (9.17E-05 Bq/atom) is used in 2-day calculations.

[g]Specific activity of 55.4-min Te-133m precursor used in calculations.

[h]Specific activity of 18.3-min Ba-141 precursor (6.32E-04 Bq/atom) is used in 2-day calculations.

[i]Specific activity of 18-min La-143 precursor used in calculations.

[j]Specific activity of 12-min Pr-147 precursor (9.63E-04 Bq/atom) is used in 2-day calculations.

[k]Specific activity of 1.73-h Nd-149 precursor used in calculations.

[l]Specific activity of 13-min Nd-151 precursor used in calculations.

[m]Specific activity of 23.4-min U-239 precursor used in calculations.

[n]Product of decay of a precursor produced directly in fission.

[o]Additional contribution from decay of Ge-77 (buildup-decay factor = 2.90) must be included.

[p]Additional contribution from decay of Zr-95 via Nb-95m (buildup-decay factor = 6.57E-03; branching ratio = 0.0074) must be included.

[q]Additional contribution from decay of Sn-125 (buildup-decay factor = 1.47E-03; branching ratio = 0.231) must be included.

[r]Additional contribution from decay of Sn-125 via Sb-125 (buildup-decay factor = 1.55E-05) must be included.

[s]Additional contribution from decay of Sb-127 via Te-127m (buildup-decay factor = 5.64E-03; branching ratio = 0.1659) must be included.

[t]Additional contribution from decay of Te-129m (buildup-decay factor = 1.00E+00; branching ratio = 0.629) must be included.

[u]Additional contribution from decay of Sb-131 (buildup-decay factor = 2.09E+35; branching ratio = 0.07) must be included.

[v]Additional contribution from decay of Sb-131 via Te-131m (buildup-decay factor = 4.33E-03; branching ratio = 0.0155) must be included.

[w]Multiple contributions from decay of Sb-131, Te-131m, and Te-131 (6 decay pathways; see Table A.2).

[x]Activity of Y-91 calculated from fission yield of Sr-91 and specific activity of Y-91 (1.37E-07 Bq/atom)..

[y]Additional contribution from decay of Zr-95 via Nb-95m (buildup-decay factor = 3.21E-07; branching ratio = 0.0074) must be included.

[z]Activity of Te-129m calculated from fission yield of Sb-129 and specific activity of Te-129m.

Table A.2. Decay relationships used in calculating activity of I-131 produced in fission

Nuclide	Half-life	λ (h^{-1})	Specific activity (Bq/atom)	Decay pathway	Branching ratio	2-day buildup-decay factor
Sb-131	23 m	1.81E+00	5.02E-04	Sb-131→Te-131→I-131	0.93	1.68E-03
				Sb-131→Te-131m→I-131[a]	0.07	1.20E-03
Te-131m	30 h	2.31E-02	6.42E-06	Te-131m→I-131	0.778	2.85E-01
				Te-131m→Te-131→I-131	0.222	9.37E-02
Te-131	25.0 m	1.66E+00	4.62E-04	Te-131→I-131	1	8.49E+31
I-131	8.04 d	3.59E-03	–	–	–	–

[a]Decay pathway Sb-131→Te-131m→Te-131→I-131 was merged with this pathway to obviate the need to deal with a 4-member decay chain. This simplification is justified when influence of short-lived Te-131 decay product on I-131 activity is expected to be negligible, give that its half-life is about 1% of that for Te-131m and about 0.2% of that for I-131.

Table A.3. Fission yields and activities of radionuclides after 2 days of decay[a]

Nuclide	Fission yield (atoms per fission) U-235 n_f	Fission yield (atoms per fission) Pu-239 n_f	Fission yield (atoms per fission) U-238 n_f	Fission yield (atoms per fission) U-238 n_{14}	Activity (Bq/fission) U-235 n_f	Activity (Bq/fission) Pu-239 n_f	Activity (Bq/fission) U-238 n_f	Activity (Bq/fission) U-238 n_{14}
Ge-77	1.19E-04	6.09E-05	1.08E-05	1.15E-04	1.07E-10	5.46E-11	9.69E-12	1.03E-10
As-77	1.99E-04	6.50E-05	2.23E-05	1.97E-04	7.28E-10	2.95E-10	7.50E-11	7.14E-10
Sr-89	4.37E-02	1.73E-02	2.76E-02	2.92E-02	6.75E-09	2.67E-09	4.26E-09	4.51E-09
Sr-90	5.47E-02	2.05E-02	3.25E-02	3.19E-02	4.20E-11	1.58E-11	2.50E-11	2.45E-11
Y-90					1.70E-11	6.38E-12	1.01E-11	9.92E-12
Sr-91	5.73E-02	2.51E-02	4.04E-02	3.87E-02	3.50E-08	1.53E-08	2.47E-08	2.36E-08
Y-91m					2.20E-08	9.64E-09	1.55E-08	1.49E-08
Y-91					7.49E-09	3.28E-09	2.13E-10	5.06E-09
Sr-92	5.84E-02	3.02E-02	4.31E-02	3.88E-02	1.94E-11	1.00E-11	1.43E-11	1.29E-11
Y-92					1.06E-09	5.49E-10	7.83E-10	7.05E-10
Y-93	6.25E-02	3.82E-02	4.91E-02	4.53E-02	4.42E-08	2.70E-08	3.47E-08	3.21E-08
Zr-95	6.43E-02	4.67E-02	5.14E-02	4.89E-02	7.89E-09	5.73E-09	6.31E-09	5.73E-09
Nb-95m					1.91E-11	1.39E-11	1.52E-11	1.39E-11
Nb-95					2.93E-10	2.13E-10	2.34E-10	2.13E-10
Zr-97	6.00E-02	5.27E-02	5.56E-02	5.28E-02	9.55E-08	8.39E-08	8.85E-08	8.40E-08
Nb-97m					9.04E-08	7.94E-08	8.38E-08	7.96E-08
Nb-97					1.03E-07	9.03E-08	9.52E-08	9.04E-08
Mo-99	5.94E-02	5.98E-02	6.17E-02	5.71E-02	1.05E-07	1.05E-07	1.09E-07	1.01E-07
Tc-99m					1.01E-07	1.02E-07	1.05E-07	9.74E-08
Ru-103	3.24E-02	6.83E-02	6.28E-02	4.62E-02	6.38E-09	1.34E-08	1.24E-08	9.09E-09
Rh-103m					6.36E-09	1.34E-08	1.23E-08	9.07E-09
Ru-105	1.20E-02	5.36E-02	4.05E-02	3.22E-02	2.90E-10	1.30E-09	9.79E-10	7.78E-10
Rh-105m					7.11E-11	3.17E-10	2.40E-10	1.91E-10
Rh-105					2.91E-08	1.30E-07	9.83E-08	7.81E-08
Ru-106	5.32E-03	4.36E-02	2.49E-02	2.45E-02	1.15E-10	9.46E-10	5.40E-10	5.32E-10
Rh-106					1.15E-10	9.46E-10	5.40E-10	5.32E-10
Pd-109	8.15E-04	1.04E-02	2.52E-03	1.12E-02	9.92E-10	1.27E-08	3.07E-09	1.36E-08
Ag-109m					9.92E-10	1.27E-08	3.07E-09	1.36E-08
Ag-111	4.24E-04	3.56E-03	7.10E-04	9.89E-03	3.79E-10	3.18E-09	6.35E-10	8.85E-09
Pd-112	3.77E-04	1.89E-03	5.59E-04	1.03E-02	6.89E-10	3.45E-09	1.02E-09	1.88E-08
Ag-112					8.16E-10	4.09E-09	1.21E-09	2.23E-08
Ag-113	2.93E-04	1.15E-03	4.15E-04	8.23E-03	2.00E-11	7.85E-11	2.83E-11	5.62E-10
Cd-113m	3.82E-06	1.49E-05	5.39E-06	1.07E-04	6.13E-15	2.39E-14	8.65E-15	1.72E-13
Cd-115m	2.80E-05	6.73E-05	3.11E-05	7.09E-04	4.88E-12	1.17E-11	5.42E-12	1.24E-10
Cd-115	3.11E-04	7.47E-04	3.44E-04	7.86E-03	6.05E-10	1.45E-09	6.69E-10	1.53E-08
In-115m					6.58E-10	1.58E-09	7.28E-10	1.66E-08
Sn-121	3.67E-04	6.20E-04	3.69E-04	8.33E-03	7.64E-10	1.29E-09	7.68E-10	1.73E-08
Sn-123	3.96E-05	2.00E-04	3.33E-06	4.65E-05	2.43E-12	1.23E-11	2.05E-13	2.86E-12
Sn-125	4.14E-04	1.18E-03	2.64E-04	6.36E-03	2.98E-10	8.50E-10	1.90E-10	4.58E-09
Sb-125	6.80E-04	1.78E-03	4.85E-04	1.20E-02	5.83E-12	1.54E-11	4.12E-12	1.02E-10
Te-125m					3.29E-14	8.69E-14	2.32E-14	5.72E-13
Sb-126	1.37E-04	3.86E-04	7.58E-05	1.91E-03	7.93E-11	2.23E-10	4.39E-11	1.11E-09
Sb-127	3.06E-03	5.01E-03	1.36E-03	1.49E-02	4.55E-09	7.45E-09	2.02E-09	2.22E-08
Te-127					4.00E-09	6.54E-09	1.78E-09	1.95E-08
Te-127m					1.08E-11	1.77E-11	4.81E-12	5.27E-11
Sb-128	5.34E-05	3.87E-04	1.47E-05	1.39E-03	2.92E-11	2.12E-10	8.04E-12	7.60E-10

Table A.3 (continued)

Nuclide	Fission yield (atoms per fission) U-235 n_f	Fission yield (atoms per fission) Pu-239 n_f	Fission yield (atoms per fission) U-238 n_f	Fission yield (atoms per fission) U-238 n_{14}	Activity (Bq/fission) U-235 n_f	Activity (Bq/fission) Pu-239 n_f	Activity (Bq/fission) U-238 n_f	Activity (Bq/fission) U-238 n_{14}
Sb-129	8.35E-03	1.45E-02	1.01E-02	2.05E-02	1.90E-10	3.30E-10	2.30E-10	4.67E-10
Te-129					4.16E-10	7.23E-10	5.03E-10	1.02E-09
Te-129m					3.19E-10	5.54E-10	3.86E-10	7.83E-10
I-130	1.71E-05	2.89E-05	4.06E-12	3.15E-05	1.80E-11	3.05E-11	4.29E-18	3.33E-11
Sb-131	2.92E-02	2.89E-02	3.25E-02	3.72E-02				
Te-131m	2.24E-03	7.14E-03	3.65E-04	1.60E-03	9.12E-09	1.95E-08	5.65E-09	8.97E-09
Te-131	7.54E-04	2.51E-03	3.55E-06	9.78E-04	9.87E-10	9.77E-10	1.10E-09	1.26E-09
I-131	3.22E-02	3.88E-02	3.29E-02	3.99E-02	2.61E-08	3.03E-08	2.71E-08	3.25E-08
Te-132	4.66E-02	5.15E-02	5.13E-02	4.65E-02	7.50E-08	8.29E-08	8.25E-08	7.48E-08
I-132					7.50E-08	8.29E-08	8.25E-08	7.48E-08
I-133	6.72E-02	6.91E-02	6.76E-02	6.00E-02	1.32E-07	1.35E-07	1.32E-07	1.17E-07
I-135	6.30E-02	6.08E-02	6.94E-02	5.50E-02	1.20E-08	1.16E-08	1.32E-08	1.04E-08
Cs-136	1.17E-04	1.23E-03	9.60E-06	2.12E-04	6.42E-11	6.75E-10	5.27E-12	1.16E-10
Cs-137	6.22E-02	6.58E-02	6.05E-02	5.15E-02	4.53E-11	4.79E-11	4.41E-11	3.75E-11
Ba-137m					4.29E-11	4.53E-11	4.17E-11	3.55E-11
Ba-140	5.98E-02	5.32E-02	5.82E-02	4.61E-02	3.37E-08	2.99E-08	3.28E-08	2.59E-08
La-140					1.99E-08	1.77E-08	1.93E-08	1.53E-08
La-141	5.95E-02	5.15E-02	5.34E-02	4.38E-02	6.79E-10	5.88E-10	6.09E-10	5.00E-10
Ce-141					1.41E-08	1.22E-08	1.27E-08	1.04E-08
Ce-143	5.73E-02	4.34E-02	4.62E-02	3.91E-02	1.23E-07	9.32E-08	9.93E-08	8.40E-08
Pr-143					2.02E-08	1.53E-08	1.63E-08	1.38E-08
Ce-144	5.27E-02	3.67E-02	4.55E-02	3.72E-02	1.48E-09	1.03E-09	1.28E-09	1.04E-09
Pr-144					1.48E-09	1.03E-09	1.28E-09	1.04E-09
Pr-145	3.78E-02	3.00E-02	3.81E-02	3.00E-02	4.67E-09	3.71E-09	4.71E-09	3.71E-09
Nd-147	2.14E-02	1.99E-02	2.59E-02	2.09E-02	1.38E-08	1.28E-08	1.67E-08	1.35E-08
Pm-147	2.14E-02	1.99E-02	2.59E-02	2.09E-02	1.36E-17	1.27E-17	1.65E-17	1.33E-17
Pm-149	1.04E-02	1.24E-02	1.63E-02	1.46E-02	2.08E-08	2.48E-08	3.26E-08	2.92E-08
Pm-151	4.12E-03	7.85E-03	7.99E-03	8.01E-03	8.72E-09	1.66E-08	1.69E-08	1.70E-08
Sm-153	1.67E-03	4.26E-03	4.15E-03	3.92E-03	3.38E-09	8.61E-09	8.39E-09	7.93E-09
Eu-155	3.95E-04	2.09E-03	1.42E-03	1.55E-03	1.75E-12	9.26E-12	6.29E-12	6.87E-12
Sm-156	2.03E-04	1.53E-03	7.60E-04	1.14E-03	1.21E-10	9.10E-10	4.52E-10	6.78E-10
Eu-156					9.72E-11	7.33E-10	3.64E-10	5.46E-10
Eu-157	1.06E-04	1.06E-03	4.14E-04	8.03E-04	1.50E-10	1.50E-09	5.84E-10	1.13E-09
Gd-159	3.01E-05	3.85E-04	8.62E-05	2.60E-04	5.21E-11	6.66E-10	1.49E-10	4.50E-10
U-237	1.50E-01	1.50E-01	1.50E-01	1.50E-01	1.45E-07	1.45E-07	1.45E-07	1.45E-07
Np-239	3.00E-01	3.00E-01	3.00E-01	3.00E-01	4.30E-07	4.30E-07	4.30E-07	4.30E-07

[a]Source for fission yields: England and Rider (1994). Activities after 2 days of decay are calculated as described in text, using specific activities and mass-chain decay relationships provided in Tables A.1 and A.2.

Table A.4. Calculated activities of radionuclides after 4 years of decay[a]

Nuclide	Activity (Bq/fission) U-235 n_f	Activity (Bq/fission) Pu-239 n_f	Activity (Bq/fission) U-238 n_f	Activity (Bq/fission) U-238 n_{14}
Sr-89	1.38E-17	5.46E-18	8.71E-18	9.22E-18
Sr-90	3.81E-11	1.43E-11	2.27E-11	2.22E-11
Y-90	3.82E-11	1.43E-11	2.27E-11	2.23E-11
Y-91	2.43E-16	1.06E-16	1.71E-16	1.64E-16
Zr-95	1.10E-15	8.01E-16	8.82E-16	8.39E-16
Nb-95m	9.12E-18	6.62E-18	7.29E-18	6.93E-18
Nb-95	2.44E-15	1.77E-15	1.95E-15	1.85E-15
Ru-103	4.50E-20	9.48E-20	8.72E-20	6.41E-20
Rh-103m	4.49E-20	9.46E-20	8.70E-20	6.40E-20
Ru-106	7.42E-12	6.08E-11	3.47E-11	3.42E-11
Rh-106	7.42E-12	6.08E-11	3.47E-11	3.42E-11
Cd-113m	5.00E-15	1.95E-14	7.06E-15	1.40E-13
Cd-115m	7.08E-22	1.70E-21	7.86E-22	1.79E-20
Sn-123	9.76E-16	4.93E-15	8.21E-17	1.15E-15
Sb-125	3.19E-12	8.63E-12	2.18E-12	5.35E-11
Te-125m	7.82E-13	2.12E-12	5.35E-13	1.31E-11
Te-127	3.60E-15	5.90E-15	1.60E-15	1.75E-14
Te-127m	3.67E-15	6.01E-15	1.63E-15	1.79E-14
Te-129	1.74E-23	1.74E-23	1.74E-23	1.74E-23
Te-129m	2.77E-23	2.77E-23	2.77E-23	2.77E-23
Cs-137	4.13E-11	4.37E-11	4.02E-11	3.42E-11
Ba-137m	3.91E-11	4.14E-11	3.80E-11	3.24E-11
Ce-141	3.48E-21	3.02E-21	3.13E-21	2.57E-21
Ce-144	4.23E-11	2.95E-11	3.65E-11	2.99E-11
Pr-144	4.23E-11	2.95E-11	3.65E-11	2.99E-11
Pm-147	6.30E-11	5.86E-11	7.63E-11	6.16E-11
Eu-155	1.00E-12	5.30E-12	3.60E-12	3.93E-12

[a]Activities after 4 years of decay are calculated as described in text, using specific activities and mass-chain decay relationships from Table A.1 and fission yields from Table A.3.

Table A.5. Dose coefficients for external exposure and effective dose coefficients for internal exposure of members of the public

Nuclide	External exposure			Internal exposure	
	Skin DF (skin deposition) (Sv/h per Bq/cm^2)[a]	Effective DF (ground deposition) (Sv/h per Bq/cm^2)[b]	Skin DF (ground deposition) (Sv/h per Bq/cm^2)[c]	Effective DF (inhalation) (Sv/Bq)[d]	Effective DF (ingestion) (Sv/Bq)[d]
Ge-77	2.28E-06	3.78E-08	2.96E-07	3.70E-10	3.30E-10
As-77	1.94E-06	3.22E-10	2.03E-09	3.90E-10	4.00E-10
Sr-89	2.28E-06	8.17E-11	2.40E-07	1.00E-09	2.60E-09
Sr-90	1.83E-06	1.02E-11	5.04E-09	2.40E-08	2.80E-08
Y-90	2.40E-06	1.92E-10	3.78E-07	1.50E-09	2.70E-09
Sr-91	2.28E-06	2.44E-08	2.71E-07	1.60E-10	6.50E-10
Y-91m	3.65E-08	1.88E-08	3.43E-08	1.10E-11	1.10E-11
Y-91	2.28E-06	2.07E-10	2.49E-07	8.90E-09	2.40E-09
Sr-92	1.83E-06	4.50E-08	6.70E-08	9.80E-11	4.30E-10
Y-92	2.51E-06	9.11E-09	5.00E-07	1.80E-10	4.90E-10
Y-93	2.51E-06	3.28E-09	4.43E-07	4.20E-10	1.20E-09
Zr-95	1.37E-06	2.60E-08	3.21E-08	4.80E-09	9.50E-10
Nb-95m	1.83E-06	2.25E-09	3.92E-09	8.80E-10	5.60E-10
Nb-95	2.63E-07	2.69E-08	3.26E-08	1.80E-09	5.80E-10
Zr-97	2.28E-06	6.26E-09	2.98E-07	9.20E-10	2.10E-09
Nb-97m	4.68E-08	2.56E-08	3.89E-08		
Nb-97	2.17E-07	2.35E-08	2.00E-07	4.50E-11	6.80E-11
Mo-99	2.17E-06	5.29E-09	1.35E-07	9.90E-10	6.00E-10
Tc-99m	2.40E-07	4.03E-09	5.18E-09	1.90E-11	2.20E-11
Ru-103	6.62E-07	1.67E-08	2.22E-08	3.00E-09	7.30E-10
Rh-103m	0.00E+00	4.50E-11	2.48E-10	2.70E-12	3.80E-12
Ru-105	2.17E-06	2.77E-08	1.61E-07	1.80E-10	2.60E-10
Rh-105m	1.83E-06	2.66E-09	3.56E-09	0.00E+00	0.00E+00
Rh-105	1.48E-06	2.74E-09	6.34E-09	3.50E-10	3.70E-10
Ru-106	0.00E+00	0.00E+00	0.00E+00	6.60E-08	7.00E-09
Rh-106	2.51E-06	7.63E-09	5.11E-07		
Pd-109	1.94E-06	4.03E-10	1.03E-07	3.70E-10	5.50E-10
Ag-109m	5.14E-07	3.50E-10	3.28E-17		
Ag-111	2.17E-06	9.61E-10	9.90E-08	1.70E-09	1.30E-09
Pd-112	9.13E-07	3.96E-10	2.18E-09	8.50E-10	9.40E-10
Ag-112	2.51E-06	2.28E-08	4.97E-07	1.70E-10	4.30E-10
Ag-113	2.28E-06	3.60E-09	4.82E-07	8.50E-11	2.15E-10
Cd-113m	1.71E-06	9.47E-12	5.58E-09	3.10E-08	2.30E-08
Cd-115m	2.28E-06	8.42E-10	2.52E-07	7.70E-09	3.30E-09
Cd-115	2.05E-06	8.32E-09	8.21E-08	1.10E-09	1.40E-09
In-115m	0.00E+00	6.52E-12	7.45E-10	5.90E-11	8.60E-11
Sn-121	1.37E-06	3.78E-12	1.08E-11	2.30E-10	2.30E-10
Sn-123	2.28E-06	4.86E-09	1.71E-07	8.10E-09	2.10E-09
Sn-125	2.40E-06	1.08E-08	3.32E-07	3.10E-09	3.10E-09
Sb-125	8.45E-07	1.53E-08	2.15E-08	4.80E-09	1.10E-09
Te-125m	1.14E-06	1.30E-09	3.40E-09	3.40E-09	8.70E-10

Table A.5 (continued)

Nuclide	External exposure			Internal exposure	
	Skin DF (skin deposition) (Sv/h per Bq/cm^2)[a]	Effective DF (ground deposition) (Sv/h per Bq/cm^2)[b]	Skin DF (ground deposition) (Sv/h per Bq/cm^2)[c]	Effective DF (inhalation) (Sv/Bq)[d]	Effective DF (ingestion) (Sv/Bq)[d]
Sb-126	1.83E-06	1.00E-07	1.92E-07	2.80E-09	2.40E-09
Sb-127	2.05E-06	2.43E-08	1.03E-07	1.70E-09	1.70E-09
Te-127	1.83E-06	1.86E-10	1.94E-08	1.30E-10	1.70E-10
Te-127m	5.37E-07	4.07E-08	1.87E-09	7.40E-09	2.30E-09
Sb-128	2.51E-06	1.09E-07	2.69E-07	4.00E-10	7.60E-10
Sb-129	1.94E-06	4.97E-08	1.84E-07	2.30E-10	4.20E-10
Te-129	2.28E-06	2.16E-09	2.07E-07	3.70E-11	6.30E-11
Te-129m	1.48E-06	1.36E-09	8.17E-08	6.60E-09	3.00E-09
I-130	1.94E-06	7.56E-08	1.54E-07	6.70E-10	2.00E-09
Te-131m	1.71E-06	4.93E-08	7.92E-08	9.40E-10	1.90E-09
Te-131	2.63E-06	1.48E-08	3.01E-07	2.80E-11	8.70E-11
I-131	1.71E-06	1.35E-08	2.31E-08	7.40E-09	2.20E-08
Te-132	7.99E-07	8.21E-09	1.08E-08	2.00E-09	3.80E-09
I-132	2.17E-06	7.96E-08	2.71E-07	9.40E-11	2.90E-10
I-133	2.17E-06	2.15E-08	1.64E-07	1.50E-09	4.30E-09
I-135	2.05E-06	5.29E-08	1.74E-07	3.20E-10	9.30E-10
Cs-136	1.48E-06	7.52E-08	9.14E-08	1.20E-09	3.00E-09
Cs-137	1.60E-06	1.03E-11	9.90E-09	4.60E-09	1.30E-08
Ba-137m	2.40E-07	2.11E-08	5.94E-08		
Ba-140	1.94E-06	6.48E-09	7.02E-08	1.00E-09	2.60E-09
La-140	2.28E-06	7.78E-08	2.97E-07	1.10E-09	2.00E-09
La-141	2.40E-06	1.63E-09	3.89E-07	1.50E-10	3.60E-10
Ce-141	1.94E-06	2.66E-09	4.75E-09	3.80E-09	7.10E-10
Ce-143	2.17E-06	1.00E-08	1.44E-07	8.30E-10	1.10E-09
Pr-143	2.05E-06	2.52E-11	7.20E-08	2.40E-09	1.20E-09
Ce-144	1.02E-06	7.31E-10	9.40E-10	5.30E-08	5.20E-09
Pr-144	2.51E-06	1.36E-09	4.57E-07	1.80E-11	5.00E-11
Pr-145	2.28E-06	5.62E-10	2.84E-07	1.70E-10	3.90E-10
Nd-147	1.94E-06	5.00E-09	3.96E-08	2.40E-09	1.10E-09
Pm-147	6.16E-07	1.23E-12	4.32E-12	4.90E-09	2.60E-10
Pm-149	2.17E-06	4.07E-10	1.07E-07	7.30E-10	9.90E-10
Pm-151	1.94E-06	1.13E-08	7.45E-08	4.60E-10	7.30E-10
Sm-153	2.05E-06	2.24E-09	2.56E-08	6.30E-10	7.40E-10
Eu-155	3.31E-07	2.12E-09	2.53E-09	6.90E-09	3.20E-10
Sm-156	1.83E-06	4.21E-09	1.55E-08	2.20E-10	2.50E-10
Eu-156	2.17E-06	4.43E-08	1.82E-07	3.40E-09	2.20E-09
Eu-157	2.17E-06	9.40E-09	1.21E-07	2.80E-10	6.00E-10
Gd-159	2.05E-06	1.81E-09	6.62E-08	2.70E-10	4.90E-10
U-237	6.51E-07	4.79E-09	7.45E-09	1.90E-09	7.60E-10
Np-239	2.63E-06	5.87E-09	9.47E-09	9.30E-10	8.00E-10

Footnotes to Table A.5

[a]Dose coefficient for exposure of skin to electrons emitted by radionuclides deposited on surface of skin obtained from Kocher and Eckerman (1987).

[b]Effective dose coefficient for exposure to photons emitted by radionuclides deposited on ground surface obtained from Eckerman and Ryman (1993).

[c]Dose coefficient for exposure of skin to electrons emitted by radionuclides deposited on ground surface obtained from Eckerman and Ryman (1993).

[d]Effective dose coefficient obtained from ICRP (2002). No entry means value is not calculated by ICRP due to short half-life of radionuclide; contributions to dose following intake of longer-lived parent radionuclide are taken into account in dose coefficient for parent.

Table A.6. Dose coefficients for internal exposure of workers[a]

Nuclide	Red marrow DF (ingestion) (Sv/Bq)	Colon DF (ingestion) (Sv/Bq)	Pancreas DF (ingestion) (Sv/Bq)	Effective DF (ingestion) (Sv/Bq)	Red marrow DF (inhalation) (Sv/Bq)	Lung DF (inhalation) (Sv/Bq)	Pancreas DF (inhalation) (Sv/Bq)	Effective DF inhalation (Sv/Bq)
Ge-77	9.00E-11	7.40E-10	1.20E-10	3.30E-10	3.10E-11	1.90E-09	3.70E-11	3.60E-10
As-77	2.50E-11	2.80E-09	2.50E-11	4.00E-10	6.90E-12	2.40E-09	6.90E-12	3.80E-10
Sr-89	4.80E-09	1.40E-08	2.00E-10	2.60E-09	4.30E-09	2.00E-10	1.80E-10	1.00E-09
Sr-90	1.80E-07	1.30E-08	6.60E-10	2.80E-08	1.60E-07	6.20E-10	6.00E-10	2.40E-08
Y-90	3.70E-13	2.10E-08	1.30E-14	2.70E-09	1.20E-12	7.50E-09	4.20E-14	1.50E-09
Sr-91	1.60E-10	3.80E-09	6.80E-11	6.50E-10	1.30E-10	5.00E-11	2.90E-11	1.70E-10
Y-91m	2.20E-12	2.60E-11	9.80E-12	1.10E-11	9.70E-13	4.70E-11	2.00E-12	1.10E-11
Y-91	6.60E-12	1.90E-08	5.50E-13	2.40E-09	2.90E-09	4.70E-08	3.90E-12	6.70E-09
Sr-92	6.40E-11	2.70E-09	5.10E-11	4.30E-10	6.10E-11	3.60E-11	1.80E-11	1.10E-10
Y-92	4.80E-12	2.60E-09	9.00E-12	4.90E-10	1.90E-12	6.50E-10	2.60E-12	2.00E-10
Y-93	4.40E-12	8.30E-09	5.10E-12	1.20E-09	1.80E-12	1.50E-09	1.80E-12	4.30E-10
Zr-95	2.10E-10	5.10E-09	1.10E-10	8.80E-10	2.30E-09	2.90E-08	9.60E-10	4.50E-09
Nb-95m	2.40E-11	4.30E-09	1.20E-11	5.60E-10	3.60E-11	5.80E-09	4.30E-11	8.50E-10
Nb-95	1.80E-10	2.80E-09	1.20E-10	5.80E-10	3.20E-10	1.10E-08	3.90E-10	1.60E-09
Zr-97	1.20E-10	1.50E-08	1.00E-10	2.10E-09	7.90E-11	3.20E-09	4.70E-11	9.40E-10
Nb-97m								
Nb-97	4.10E-12	1.40E-10	1.40E-11	6.80E-11	1.70E-12	1.50E-10	3.40E-12	4.70E-11
Mo-99	5.00E-10	2.30E-09	2.70E-10	7.40E-10	2.60E-11	5.60E-09	2.20E-11	9.70E-10
Tc-99m	4.20E-12	3.70E-11	9.90E-12	2.20E-11	1.60E-12	7.20E-11	2.80E-12	1.90E-11
Ru-103	1.60E-10	4.30E-09	1.30E-10	7.30E-10	2.30E-10	2.00E-08	3.00E-10	2.80E-09
Rh-103m	5.00E-15	5.70E-12	3.30E-14	3.80E-12	1.40E-15	1.50E-11	6.30E-15	2.50E-12
Ru-105	2.20E-11	1.50E-09	3.50E-11	2.60E-10	8.40E-12	7.40E-10	1.10E-11	1.80E-10
Rh-105m								
Rh-105	1.20E-11	2.70E-09	1.10E-11	3.70E-10	4.80E-12	2.20E-09	4.60E-12	3.40E-10
Ru-106	1.50E-09	4.50E-08	1.50E-09	7.00E-09	9.60E-10	5.00E-07	1.10E-09	6.20E-08
Rh-106								
Pd-109	8.00E-13	4.10E-09	7.70E-13	5.50E-10	2.70E-13	2.00E-09	2.50E-13	3.60E-10
Ag-109m								
Ag-111	2.20E-11	9.60E-09	2.20E-11	1.30E-09	8.00E-12	1.10E-08	8.70E-12	1.70E-09
Pd-112	2.40E-10	4.60E-09	1.20E-10	9.40E-10	1.80E-10	3.40E-09	1.90E-10	8.30E-10
Ag-112	1.20E-11	2.10E-09	2.30E-11	4.30E-10	4.40E-12	5.70E-10	6.30E-12	1.80E-10
Ag-113	6.00E-12	1.05E-09	1.15E-11	2.15E-10	2.20E-12	2.85E-10	3.15E-12	9.00E-11
Cd-113m	3.50E-09	9.20E-09	3.50E-09	2.30E-08	1.80E-09	1.60E-07	1.80E-09	3.00E-08
Cd-115m	1.70E-10	1.80E-08	1.80E-10	3.30E-09	5.60E-11	5.50E-08	6.00E-11	7.30E-09
Cd-115	6.40E-11	1.00E-08	5.20E-11	1.40E-09	2.90E-11	6.20E-09	2.80E-11	1.10E-09
In-115m	4.90E-12	4.80E-10	7.50E-12	8.60E-11	3.20E-12	2.40E-10	2.40E-12	6.00E-11
Sn-121	2.30E-12	1.80E-09	2.00E-13	2.30E-10	3.60E-12	1.40E-09	3.30E-13	2.20E-10
Sn-123	2.50E-10	1.60E-08	3.30E-11	2.10E-09	8.10E-10	5.80E-08	1.10E-10	7.70E-09
Sn-125	2.10E-10	2.40E-08	4.60E-11	3.10E-09	3.40E-10	1.80E-08	7.10E-11	3.00E-09
Sb-125	1.50E-09	4.10E-09	3.80E-10	1.10E-09	1.60E-09	3.00E-08	8.30E-10	4.50E-09
Te-125m	1.70E-09	2.80E-09	6.00E-11	8.70E-10	6.80E-10	2.50E-08	3.70E-11	3.30E-09
Sb-126	9.00E-10	1.20E-08	4.80E-10	2.40E-09	6.20E-10	1.60E-08	5.90E-10	2.70E-09
Sb-127	3.00E-10	1.20E-08	1.10E-10	1.70E-09	1.20E-10	1.00E-08	6.80E-11	1.60E-09
Te-127	1.00E-11	1.10E-09	4.70E-12	1.70E-10	3.10E-12	7.00E-10	1.40E-12	1.20E-10
Te-127m	8.20E-09	6.20E-09	1.30E-10	2.30E-09	3.60E-09	5.30E-08	6.70E-11	7.20E-09
Sb-128	1.60E-10	3.80E-09	1.90E-10	7.60E-10	6.20E-11	9.60E-10	6.20E-11	4.20E-10

Table A.6 (continued)

Nuclide	Red marrow DF (ingestion) (Sv/Bq)	Colon DF (ingestion) (Sv/Bq)	Pancreas DF (ingestion) (Sv/Bq)	Effective DF (ingestion) (Sv/Bq)	Red marrow DF (inhalation) (Sv/Bq)	Lung DF (inhalation) (Sv/Bq)	Pancreas DF (inhalation) (Sv/Bq)	Effective DF (inhalation) (Sv/Bq)
Sb-129	4.20E-11	2.40E-09	6.00E-11	4.20E-10	1.70E-11	8.20E-10	2.40E-10	1.80E-11
Te-129	9.40E-13	1.20E-10	1.90E-12	6.30E-11	4.40E-13	1.40E-10	3.80E-11	5.70E-13
Te-129m	5.30E-09	1.40E-08	2.30E-10	3.00E-09	2.00E-09	4.50E-08	6.30E-09	1.10E-10
I-130	7.50E-11	1.20E-10	1.20E-10	2.00E-09	3.40E-11	5.60E-11	6.90E-10	3.00E-11
Te-131m	2.60E-10	5.90E-09	1.80E-10	1.90E-09	1.00E-10	4.30E-09	1.10E-09	8.00E-11
Te-131	1.10E-12	1.90E-11	5.30E-12	8.70E-11	5.50E-13	8.70E-11	3.80E-11	1.10E-12
I-131	1.00E-10	1.20E-10	6.10E-11	2.20E-08	3.80E-11	5.90E-11	7.60E-09	1.90E-11
Te-132	5.30E-10	1.30E-08	3.70E-10	3.70E-09	2.40E-10	9.50E-09	2.20E-09	2.20E-10
I-132	2.60E-11	4.60E-11	7.20E-11	2.90E-10	1.20E-11	3.50E-11	9.60E-11	1.50E-11
I-133	4.70E-11	1.10E-10	5.70E-11	4.30E-09	1.90E-11	4.20E-11	1.50E-09	1.60E-11
I-135	4.00E-11	7.30E-11	7.30E-11	9.30E-10	1.70E-11	4.00E-11	3.30E-10	1.80E-11
Cs-136	2.80E-09	3.40E-09	3.40E-09	3.00E-09	1.00E-09	9.80E-10	1.30E-09	1.20E-09
Cs-137	1.30E-08	1.50E-08	1.40E-08	1.30E-08	4.50E-09	4.40E-09	4.80E-09	5.00E-09
Ba-137m								
Ba-140	7.10E-10	1.70E-08	1.40E-10	2.50E-09	1.40E-09	1.50E-10	1.00E-09	1.60E-10
La-140	2.60E-10	1.30E-08	2.10E-10	2.00E-09	1.40E-10	3.70E-09	1.10E-09	1.20E-10
La-141	9.40E-13	2.00E-09	1.60E-12	3.60E-10	3.00E-12	6.20E-10	1.50E-10	1.50E-12
Ce-141	1.90E-11	5.50E-09	1.10E-11	7.10E-10	3.50E-11	2.80E-08	3.60E-09	4.20E-11
Ce-143	3.50E-11	8.30E-09	2.80E-11	1.10E-09	1.50E-11	4.60E-09	8.10E-10	1.40E-11
Pr-143	1.70E-12	9.30E-09	1.10E-14	1.20E-09	2.00E-12	1.70E-08	2.30E-09	1.30E-14
Ce-144	1.90E-10	4.20E-08	1.90E-11	5.20E-09	1.10E-09	3.90E-07	4.90E-08	2.00E-10
Pr-144	3.40E-14	1.00E-11	2.40E-13	5.00E-11	1.60E-14	5.30E-11	1.90E-11	4.10E-14
Pr-145	4.60E-13	2.60E-09	6.40E-13	3.90E-10	1.90E-13	7.10E-10	1.70E-10	2.10E-13
Nd-147	3.10E-11	8.20E-09	1.80E-11	1.10E-09	3.30E-11	1.70E-08	2.30E-09	3.20E-11
Pm-147	3.50E-11	2.00E-09	3.30E-15	2.60E-10	3.70E-10	3.60E-08	4.60E-09	5.40E-14
Pm-149	2.10E-12	7.80E-09	1.20E-12	9.90E-10	1.20E-12	4.10E-09	7.20E-10	7.20E-10
Pm-151	3.60E-11	5.20E-09	3.00E-11	7.30E-10	1.50E-11	2.40E-09	4.50E-10	1.40E-11
Sm-153	9.50E-12	5.70E-09	7.60E-12	7.40E-10	2.30E-11	3.70E-09	6.10E-10	5.20E-12
Eu-155	7.00E-11	2.20E-09	1.70E-11	3.20E-10	9.80E-09	1.70E-08	6.50E-09	1.40E-09
Sm-156	1.10E-11	1.70E-09	1.00E-11	2.50E-10	2.10E-11	1.20E-09	2.10E-10	1.20E-11
Eu-156	2.30E-10	1.50E-08	1.50E-10	2.20E-09	6.10E-10	2.10E-08	3.30E-09	3.60E-10
Eu-157	2.10E-11	4.30E-09	2.10E-11	6.00E-10	1.40E-11	1.30E-09	3.20E-10	8.70E-12
Gd-159	4.60E-12	3.70E-09	4.40E-12	4.90E-10	8.80E-12	1.40E-09	2.70E-10	2.20E-12
U-237	3.70E-11	5.70E-09	1.90E-11	7.70E-10	1.90E-11	1.30E-08	1.80E-09	2.20E-11
Np-239	2.70E-11	6.00E-09	2.00E-11	8.00E-10	4.50E-11	5.90E-09	9.00E-10	1.40E-11

[a]Dose coefficients for specific organs or tissues and effective dose coefficients obtained from ICRP (2002). No entry means value is not calculated by ICRP due to short half-life of radionuclide; contributions to dose following intake of longer-lived parent radionuclide are taken into account in dose coefficient for parent.

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